CHAPTER 8

Strategies for People, Partnerships, and Productivity

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Chapter 8
Key Findings and Recommendations

Experts interviewed by the mission-specific working groups and respondents to the Request For Information both provided highly consistent responses to the charge questions related to workforce, international partnerships, and the management and operations of BER's research enterprise. This chapter consolidates the entire subcommittee's Key Findings and Recommendations that emerged from these responses.

Key Findings

PEOPLE

KF8.1 BER funds academic scientists across the nation who contribute exceptional talent and new expertise to the program's mission.

KF8.2 The DOE national laboratory complex provides many positive career opportunities for BER-funded scientists.

KF8.3 Programs for undergraduates, graduate students, and postdoctoral students effectively recruit scientific talent for BER missions.

KF8.4 The lack of workforce diversity significantly limits BER's long-term leadership and the necessary growth of its scientific workforce.

KF8.5 BER frontier research successes and impacts lack visibility.

KF8.6 BER funding for high-risk discovery science and paths to independent work are rare at the national laboratories, and increased funding flexibility is desired at all career levels.

KF8.7 Real and perceived volatility in funding levels and research topics hampers workforce recruitment and retention at all career stages and impedes long-term productivity.

KF8.8 Current funding models produce high levels of professional anxiety among national laboratory programmatic staff who feel pressure to continuously secure projects that support their own salaries.

KF8.9 At some user facilities, limited opportunities exist for support staff advancement, independent research, and future career choices, leading to overwork and professional burnout. These challenges vary significantly depending on the operational model of a given facility.

KF8.10 Over the last decade, BER has seen attrition of scientific workforce talent, particularly among academic Early Career Research Program awardees, half of whom are no longer funded in the BER mission space.

KF8.11 Some BER-supported Early Career awards are limiting workforce development due to their timing and topical volatility, providing only narrow windows of opportunity in a scientist's career pathway. This impact is more pronounced for the Earth and Environmental Systems Sciences Division than the Biological Systems Science Division and its more stable approach.

PARTNERSHIPS

KF8.12 Although international collaborations are critical for strengthening BER scientific output and increasing global visibility, such partnerships are difficult for BER-funded institutions due to funding restrictions between countries.

KF8.13 BER program staff and BER-supported scientists have few resources to travel or engage internationally.

KF8.14 Meeting societal needs requires more domestic and international collaborations for ground-based observations and high-resolution Earth system modeling to improve research outcomes and ensure integration of efforts.

KF8.15 Because of its mobile facilities and ability to fund international partners, the Atmospheric Radiation Measurement (ARM) user facility excels in collaborations—both in the United States and abroad.

PRODUCTIVITY

KF8.16 BER user facilities are specially positioned to integrate researchers across BER because of their unique expertise, leadership positions, and ability to attract users.

KF8.17 The Bioenergy Research Center (BRC) program achieves strategically important BER mission goals, and its model could be applied to other relevant research areas, such as environmental microbiomes. With their integrative focus, the BRCs have excelled at building impactful and highly productive researcher networks working toward a common goal.

KF8.18 BER should maintain team-based projects combining researchers from academic institutions and DOE national laboratories.

KF8.19 Silos and mission boundaries within DOE and across agencies block the potential for science accomplishments to inform innovation and applied solutions.

KF8.20 U.S. agencies should consider opportunities to expand collaborative climate science research beyond the current facilitating role of the U.S. Global Change Research Program, which lacks allocated funding.

Recommendations

PEOPLE

R8.1 Incentivize efforts to increase workforce diversity and provide a culture of inclusivity, explicitly measuring successes and evaluating outcomes continually for further improvements using processes with broad participation.

R8.2 Invest in effectively communicating BER scientific successes and proactively convey the importance of the program's research mission to better recruit and retain top global talent.

R8.3 Support Early Career award researchers in their future and post-award career paths by providing training and opportunities for research leadership.

R8.4 Provide incentives to the national laboratories for creating and sustaining professional development opportunities for early and mid-career scientists.

R8.5 Develop and demonstrate balanced models for providing BER-supported researchers with options for both collaborative teaming paths and individual successes.

PARTNERSHIPS

R8.6 Enhance international partnerships and cross-agency cooperation by developing new funding modalities, such as joint calls with the National Science Foundation and other agencies.

R8.7 Increase opportunities for BER program managers and supported scientists to engage with their international counterparts.

R8.8 Develop new international programs and consider establishing a formal office for international activities.

R8.9 Increase fellowships, scholarships, and international exchange opportunities.

R8.10 Optimize resources and efficiencies by bridging across agencies and nations.

PRODUCTIVITY

R8.11 Promote more effectively BER's world-class programs; unique facilities; and leadership in creating synergies across observations, process studies, and system modeling.

R8.12 Secure leadership in both the science areas where BER already excels (e.g., observation and modeling integration) and in new growth areas.

R8.13 Assign facilities the responsibility of coordinating and storing the data relevant to their main area of expertise.

R8.14 Increase emphasis in modeling activities related to uncertainty quantification and uncertainty propagation for complex, multiscale systems.

R8.15 Build a productive, creative workforce by supporting interdisciplinary research opportunities for early and mid-career scientists, as is done by crosscutting organizations such as the Max Planck Institutes in Europe or Chinese institutes for environmental and climate science.

R8.16 Manage volatility, potential and realized, in funding levels and award topics.

R8.17 Use inter- and intra-agency cooperation and co-funding to foster interdisciplinary collaborations, maximize large-scale resources, and bridge Technology Readiness Levels (TRLs).

R8.18 Create a culture of communication and interaction across the TRL spectrum in DOE and among BER, businesses, and nongovernmental organizations.

R8.19 Develop integrative science opportunities as a signature area for BER.

8 Strategies for People, Partnerships, and Productivity

8.1 Inspiring Researcher Engagement with BER Missions

Multiple U.S. and international respondents defined leadership as "producing the next generation of scientists." BER could lose its international leadership irrevocably without a pipeline of the best and brightest talent to engage in the program's mission areas. Competition for this talent is international and increasingly intense between public and private institutions in rapidly emerging science and technology areas relevant to BER. The quickly evolving and highly competitive nature of ensuring next-generation scientific leadership raises important questions:

- How can BER increase its talent pool to represent the full diversity of the United States?
- How can BER best inspire and sustain academic researchers to dedicate their careers to BER science missions?
- What role can BER play to enhance desirable career tracks within the national laboratory complex for early, mid-career, and senior scientists and engineers?
- How does BER best communicate its frontier research successes to be a national and global attractor and recruiter of top prospects?

8.1.1 Increasing Workforce Diversity

BER needs new strategies to encourage underrepresented groups to pursue careers in the program's research areas. Positive first steps are the recent investments in programs such as Reaching a New Energy Science Workforce and Funding for Accelerated Inclusive Research, which seek to engage faculty and students from minority-serving institutions. However, these investments need growth and longevity. Another area of needed improvement is BER's current workforce diversity. The national laboratories now have a collection of best practices in diversity, equity, and inclusion (DEI) and many are quantitatively assessing their current support of these principles, setting goals, and designing strategies to meet them through careful allocation of resources (Gibbs and Wagner 2021; U.S. DOE 2021c; U.S. DOE 2022c, d). Evaluations are needed for funding and hiring processes to ensure that they consider and incorporate DEI best practices. Also needed are support systems to establish equal opportunities for the career progression of underrepresented minorities.

Program design, contracting, and staff training represent other opportunities to reduce barriers to engaging underrepresented groups in BER science. Respondents generally perceive the panel review process for grants as fair, and program managers are commended for their appreciation of diversity of thought and scientific experience. Suggestions for improving DEI within BER's purview include (1) setting standards for evaluating funding opportunities to reduce implicit bias, (2) requiring diversity on panels, (3) collecting data on diversity trends within BER-funded science, and (4) evaluating national laboratory hiring practices and efforts to engage underserved communities.

BER also might consider providing supplemental support to funded projects to specifically recruit and train a diverse workforce. The National Institutes of Health (NIH) and National Science Foundation (NSF) explicitly support underrepresented groups through dedicated resources to advance DEI goals, and large center-scale proposals at other agencies require balance in leadership positions and engagement with minority-serving institutions. BER could adopt similar approaches to amplify current DEI efforts.

Bureaucracy and restrictions related to establishing collaborations with international researchers for DOE projects can hinder BER leadership in both science and diversity, according to concerns raised by some interviewees and respondents to the Request For Information (RFI). One respondent stated that the requirements for bringing a foreign national into a DOE project "create a culture of mistrust" and frustrate those who are required to implement the requirements.

8.1.2 Enhancing Career Development

Support for, and the approach to, workforce development is necessarily different at national laboratories and universities. University researchers typically enjoy more academic freedom. They receive relatively short-term funding, and awards are commonly made to single investigators or small teams, which creates ample opportunities for distinguishing the intellectual leadership and contributions of individuals (especially for early career researchers). In contrast, national laboratories are funded to engage in mission-driven discovery science. They receive longer-term funding as part of large multidisciplinary teams. Although national laboratories succeed in attracting and training talented early career scientists, including postdocs and PhD students, respondents expressed concerns about the retention of theses scientists, given the limited opportunities for leadership and unique intellectual contributions on large teams (see Case Study: Can BER Influence National Laboratory Culture to Attract Great Talent?, p. 127). These same issues potentially limit DOE's ability to attract more senior scientists and diversify its workforce across all career stages. Also, many respondents noted the difficulty in disentangling the role of the DOE Office of Science from that of the national laboratories as it relates to workforce and career development.

Senior and Mid-Career Scientists

Respondents shared many perspectives on potential challenges that national laboratories face in recruiting and retaining world-leading senior scientists in BER research areas. These challenges include volatility in funding levels and priorities that restrict scientists' freedom to explore new ideas. Encouraging a less restrictive research environment with more opportunities for investigating new topics and establishing collaborations and joint appointments with universities are potential ways to simultaneously retain young scientists and attract more senior researchers. Continuity of funding and the ability to focus on scientific areas of interest are key components of research success and job satisfaction.

At user facilities in particular, staff scientists have limited time to devote to their own areas of research interest. BER might consider reducing caps on time committed to laboratory-directed research and development (LDRD) projects, providing more time for individual research at user facilities, better supporting travel to conferences, and creating more opportunities for discovery science.

According to respondents, there is a perception that DOE-funded researchers risk losing clear scientific identities and face limited career options (including work with other agencies or transitions to academia) the longer they are supported by DOE. Another perceived limitation is the lack of opportunities for independent work, partly because scientists are required to charge their time by the hour to prescribed tasks within some BER-funded projects that do not allow exploratory or collaborative research outside strictly defined areas. This practice, which is not typical in academia, is frequently referenced as overly restrictive for scientists choosing between a university or DOE national laboratory career. Although BER's very large-scale collaborative grants offer the benefits of unique, sustained, and multidisciplinary team science, mid-career researchers in these projects face challenges trying to distinguish themselves scientifically and expand their leadership roles.

Respondents suggested that single principal investigator (PI) or small-team grants could stimulate creativity and innovation while providing opportunities for mid-career scientists to distinguish themselves. They also noted that the number of such grants likely would be limited by the staffing levels of BER program

Continued on p. 128

CASE STUDY

Can BER Influence National Laboratory Culture to Attract Great Talent?

The DOE national laboratories represent one of the world's premier research infrastructures. Their greatest asset, though, is their people who are inspired by the opportunity to shepherd an energy transition, combat climate change, build sustainable prosperity, and guard nuclear security. Succeeding in these missions requires DOE and its national laboratories to be equally vested in the success of these people.

America is experiencing a post-pandemic shift in work culture. The zeitgeist is captured by Adria Horn, a military veteran, in an article from McKinsey Consulting: "The emotional ties that may have bound people together during the pandemic work period have waned, and now they will seek opportunities not only to unpin their clipped wings but to fully expand them in ways that they wouldn't have let themselves do previously." In a 6-month study in 2021, 40% of employees who left their job did not have another one lined up. McKinsey Consulting found a profound disconnect between the reasons these employees gave for leaving their jobs and the reasons their employers thought they left (De Smet et al. 2021; see figure, this page). Beyond better pay or the ability to work remotely,

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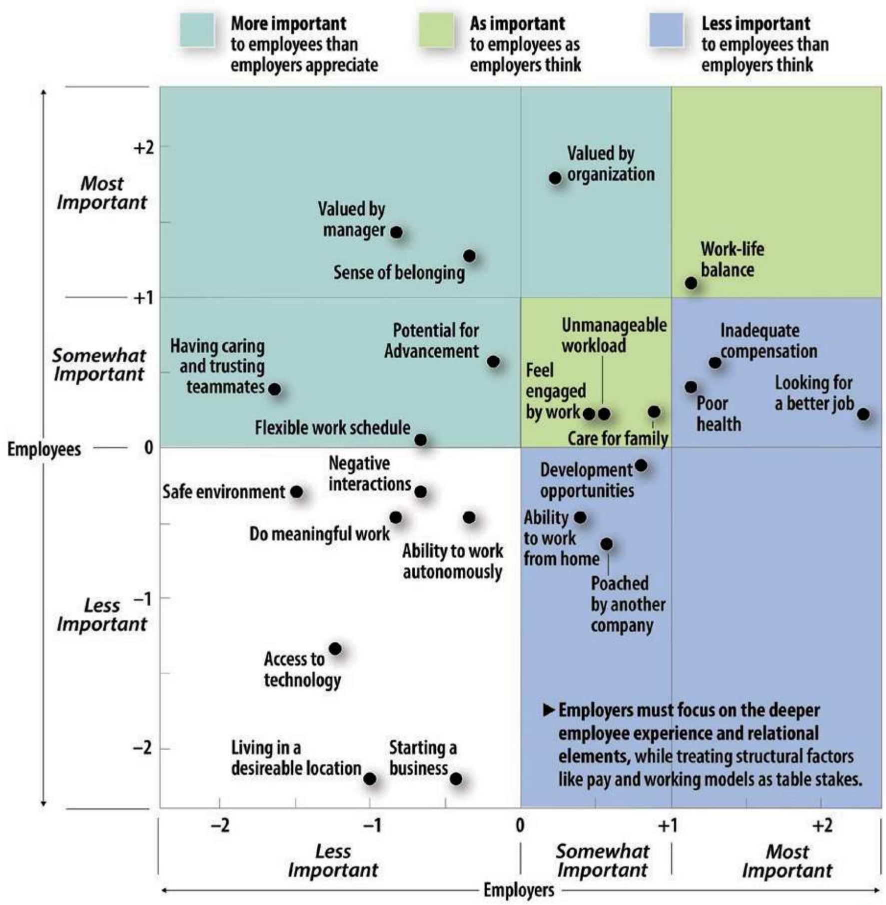

Employer and Employee Perspectives on What Matters Most. This graph highlights differences in factors that employees and employers viewed as important during a 2021 workplace study. Employers tended to overlook relational elements that were key drivers of employees leaving the workforce, such as lack of belonging or feeling valued at work. [Reprinted by permission from Exhibit 5 from "Great Attrition or Great Attraction? The Choice is Yours," September 2021, McKinsey Quarterly. www.mckinsey.com. ©2022 McKinsey & Company. All rights reserved.]

CASE STUDY

Continued from previous page

employees want to feel valued, have a sense of belonging, be part of a team that cares about them, and have a pathway to advance. The take-home message of the study is that employers that recognize and adjust to this cultural shift in the workplace will have a competitive advantage in recruiting and retaining talent.

Within the national laboratory system, some staff have opportunities for professional advancement and some feel engaged and included in laboratory objectives, according to respondents. However, management quality is inconsistent, and national laboratory staff are experiencing considerable burnout and high levels of anxiety due to the current funding model's pressure on programmatic staff to continuously find projects that support their own salaries. Similarly, respondents report that few opportunities exist for advancement or independent research at some user facilities and that facility support staff are overworked, risk professional burnout, and face limited future career choices.

There is no reason to assume that national laboratories are immune from the cultural shifts that will contribute to either great attrition or great attraction in the U.S. workplace. But what if the national laboratories were positioned to be great attractors of global talent? BER and DOE should consider how to influence the culture and climate across the national laboratory system to promote inclusivity, improve opportunities for personal and professional development, and mitigate sources of stress and anxiety.

Imagine if the best and brightest global talent could be engaged in DOE missions because national laboratories are known as destinations that value and support every employee. Imagine a future workforce that is creative, empowered, and characterized by a deep sense of community and belonging while energized to solve the grand challenges of our time. Imagine what could be achieved by driving professional development throughout the national laboratory workforce and "unpinning those clipped wings."

Takeaway

DOE and the national laboratories need to prioritize, with time and investment, workforce development.

Continued from p. 126

managers. Setting baselines for grant size would be important, with several respondents suggesting the grants minimally support 1.5 to 2 full-time equivalents.

Mid-career development strategies at other agencies or institutions might serve as useful examples of potential opportunities. Some NSF grant mechanisms allow mid-career scientists to pivot their research programs and partner with mentors to change or evolve their research focus. The Netherlands take a long-term approach to mid-career development through their Vici Talent Programme, which is similar to the Office of Science's Early Career Research Program (ECRP) but provides grants to outstanding mid-career scientists. DOE could consider a similar approach for developing more opportunities for mid-career researchers.

Workforce development is largely the responsibility of the national laboratories. However, BER can play a more active role in this process by offering an array of smaller grant opportunities across all career stages while also integrating assessments of workforce development into its major collaborative grants (e.g., the triennial reviews of Science Focus Areas).

Early Career Scientists

The ECRP is an effective way to recruit, support, and train the next generation of scientists, according to many respondents. These prestigious awards are

critical investments, both scientifically and in terms of workforce development. Although respondents favorably view ECRP (with one noting that many other agencies lack comparable programs), they offered suggestions for improvement. For example, BER could (1) better advertise the program to ensure all eligible applicants know about the opportunity and (2) lengthen the time between when proposals are requested and when they are due.

BER's two divisions—the Biological Systems Science Division (BSSD) and the Earth and Environmental Systems Sciences Division (EESSD)—implement the ECRP request for proposals differently. In EESSD, ECRP topics are often very narrow and rotate among the program areas in a manner that limits consistency and continuity. EESSD is limiting its ability to capture novel and transformative ideas by overly restricting the focus of its ECRP requests for proposals, according to some respondents. As a result, early career researchers may only have one opportunity in their careers to apply for ECRP awards when their expertise, ideas, and eligibility align with the request for proposals. Another effect of BER's current ECRP approach is that proposals typically do not suggest science that crosses BER organizational boundaries.

Narrow definitions of an "early career researcher" may have unintended consequences. For example, the American Society of Plant Biologists noted, "one eligibility criterion for the ECRP award—the number of years from gaining a PhD—should be reconsidered, given the different paths today's scientists take to a faculty position (time in industry, multiple degrees, career-life balance decisions, etc.)."

BER investments in ECRP scientists do not realize their full value unless awardees have clear professional development pathways beyond their initial grants. Respondents noted the challenge for national laboratories in aligning their ECRP candidates with internal succession planning. Unlike universities, national laboratories need to find other projects that can support their Early Career award winners once their grants end. As a result, some national laboratories filter ECRP candidates, potentially limiting the range of ideas presented to BER.

Several ECRP awardees also noted difficulties in remaining in the BER community after their projects end because of a lack of funding opportunities. This challenge highlights the need to train early career scientists to write competitive proposals for the mission-driven science that BER supports. Some national laboratories already support development of proposal-writing skills, but these efforts are perhaps not as widespread as they could be.

Again, several respondents suggested that BER dedicate funds to a small-grants program that might support exploratory research beyond narrowly defined mission-oriented topics. Such grants would provide early career researchers with time to develop proposal-writing skills and experience in leading, conducting, and managing their own projects. Ideally these small grants also could serve as transitions back toward large, ongoing mission-oriented research projects. Other potential strategies for improving retention of early career scientists include:

- Recognizing researchers for their overall contribution as opposed to their impact on a single project.
- Retaining senior scientists who can collaborate with early career scientists.
- Promoting organizations and research success stories at large conferences.
- Adjusting funding mechanisms (see "Funding Cycles for Projects and User Facilities" section, this page).
- Incentivizing the development of university courses targeting the skills needed for BER-focused research.

Funding Cycles for Projects and User Facilities

The frequency and duration of BER funding cycles for projects and user facility support can pose particular challenges for both early and mid-career researchers. BER funding cycles can throw researchers' career development off track if they miss applying for an annual or even less-frequent funding opportunity or user facility call due to life events such as child or parental leave. Knowing in advance when calls for

proposals will be announced would help PIs, along with establishing rolling funding opportunities that could support off-cycle ideas and enable researchers to reset their careers after life disruptions.

In addition, respondents strongly viewed 3-year, nonrenewable funding cycles as problematic. Such cycles are incompatible with the funding of graduate students, since obtaining a doctorate takes substantially longer than 3 years in the United States. In contrast, BER ECRP awards are typically 5 years, a duration enabling PIs to be more creative, innovative, and ambitious. Other potential funding durations and structures to consider include (1) 3-year grants that are renewable or explicitly intended as seed projects for downselecting and then launching larger collaborative projects or (2) 10-year grants with decisions on funding continuation in year 5. Japan has good examples of these types of structures that DOE might review and evaluate.

Training the Non-PhD Workforce

BER's impact from supporting the training of PhD students and postdoctoral researchers is significant. However, the program's national and international leadership is not solely contingent on people with doctoral degrees. Competition and demand are and will continue to be high for specialized staff who can operate facilities, manage them, and support and use cutting-edge emerging technologies, such as artificial intelligence, edge computing in cyber-physical systems, and quantum computing. An increased focus on individuals with bachelor's or master's degrees likely will be warranted, subject to specific staff roles and focus. Consequently, specialist programs, including practicum training such as those found in Germany and Japan, will be more important than doctoral-level theory. Example practicums could involve sensing, control systems, the use of feedstocks in conversion processes, and software engineering with embedded intelligence. A powerful approach to implementing these practicums might include demonstration facilities at national laboratories in partnership with community colleges and the private sector.

BER could potentially enhance workforce development in several ways. NSF and NIH both have strong programs to support workforce development, including sponsored internships for students to work in nonacademic settings. Similar opportunities for DOE laboratory personnel may enhance opportunities for innovation.

8.1.3 Developing a Communications Strategy for Workforce Recruitment

Respondents raised several issues regarding BER's communication strategies. Although many example achievements substantiate BER's scientific leadership, the scientific community generally does not associate these successes with the program. This lack of visibility, both nationally and internationally, has implications for workforce recruitment and for communicating BER's success stories to audiences including Congress, stakeholders, and the public.

BER needs to become more visible and accessible, according to several respondents representing the continuum of BER science. Academic PIs and their partners interact, experience, and perceive BER in a fundamentally different way than those within the national laboratory complex. Many researchers feel that BER-funded science is not fully open, that there is an "in crowd," and that they lack the knowledge to break into the program's mission-driven funding environment. These are major challenges to engaging underrepresented minorities and achieving diversity, equity, and inclusion within BER programs. The BERAC subcommittee identified two primary barriers to expanding BER science collaborations within the broader scientific community. Both involve a lack of understanding of (1) how non-BER scientists can receive funding and thereby contribute to DOE missions or (2) how non-BER and BER scientists can access novel DOE resources and capabilities.

Although some annual funding opportunity announcements (FOAs) specifically target the academic science community, many in that community do not fully understand how FOA priorities emerge or how best to formulate a FOA response aligned with Office of Science missions. Clear guidance is needed that

describes ways to engage DOE programs, explains DOE mission-oriented culture, and outlines strategies for working with DOE scientists as potential collaborators. BER programs hold town hall events at large conferences (e.g., the American Geophysical Union's annual fall meeting), but additional guidance from and access to program managers (e.g., online office hours) would directly benefit researchers unable to attend conferences.

Another barrier scientists can face is gaining access to DOE resources, such as novel instrumentation, laboratories, and field platforms, that can advance their science—a challenge that surprisingly confronts both academic and national laboratory researchers. A research group must often write two proposals: one to conduct the proposed science and another to use unique equipment or capabilities at a DOE user facility. However, independent groups that review both proposals often conclude that neither proposal is worth supporting unless the other one is (a scientific catch-22). This challenge is compounded by different timelines and different decision-makers involved for both proposals.

Some user facilities, such as the Environmental Molecular Sciences Laboratory (EMSL), regularly reach out to the broader scientific community to explain how their administrative and technical systems work and to provide points of contact and collaboration between facility staff and potential users. Additional workshops or online presentations would prove useful from other Office of Science–funded facilities that provide tools that support BER science. Another consideration is whether facilities following a centralized model (e.g., single, large user facilities) provide equal access across the community. Some capabilities, including automation and data science, could benefit more users if they were regionally distributed across the United States.

In summary, BER needs improved communication strategies to retain its talented workforce, engage new constituencies in its mission space, and continue to attract global talent.

8.2 Opportunities for International Partnerships

The charge letter for the BERAC subcommittee's benchmarking effort outlines "international competitiveness" as a central focus, but respondents strongly cautioned against a strict adversarial framing of BER's leadership relative to international peers. As noted by the National Science Board's Vision 2030 report, BER must acknowledge that sustained leadership requires strongly engaging in ". . . a truly worldwide enterprise, with more players and opportunities from which humanity's collective knowledge is growing rapidly" (NSB 2020).

This collaborative perspective is particularly significant given BER's central role in addressing the emerging bioeconomy, climate change, and sustainable prosperity—all of which will fundamentally shape the future of the global collective commons. These issues cannot be adequately addressed by a single nation, much less a single U.S. agency. Environmental system science, climate science, and Earth system modeling exemplify the need for and importance of enhancing domestic and international collaborations to accelerate research impacts (see Fig. 8.1, p. 132). The scientific challenges associated with each research area require assembling teams with diverse expertise; leveraging national and regional field campaigns and data; and implementing enhanced, cross-agency and international funding mechanisms.

BER's Atmospheric Radiation Measurement (ARM) user facility and Atmospheric System Research (ASR) program have achieved notable successes in international and domestic partnerships. For example, ARM demonstrated significant leadership in supporting and internationally coordinating the Polarstern cruises during the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) polar expedition (see Case Study, p. 133). Experts noted that ARM and ASR are two of only a few BER programs to fund international partners, an activity they say should be maintained.

ARM's three mobile facilities represent another significant collaborative strength, enabling scientists to

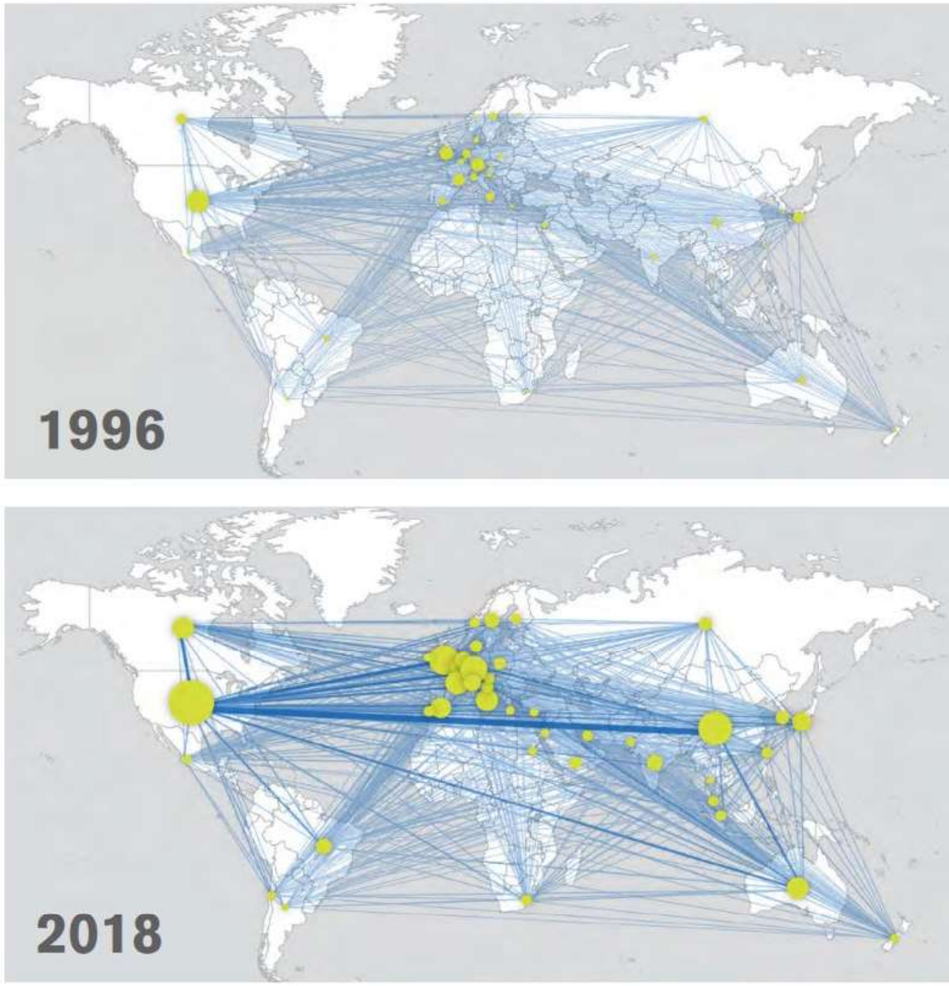

Fig. 8.1. International Collaboration Among Researchers Grows Dramatically. Collaboration among scientists and engineers around the world enhances research capacity. In 1996, U.S. researchers most frequently co-authored papers with researchers in Europe and Japan. In 2018, these connections grew, as shown by the width of the lines and the size of the circles, which denote relative number of publications. China has emerged as the single most frequent partner with the U.S. research community. [Courtesy National Science Foundation]

propose field campaigns to use these facilities to collect atmospheric and climate data from undersampled regions around the world. Proposals are open, and those submitted by consortiums have increased chances of funding. These exemplary capabilities clearly demonstrate BER's commitment to international collaboration for research observations. Domestically, the ARM Tracking Aerosol Convection Interactions Experiment (TRACER) campaign represents BER leadership through cross-agency coordination with NASA and NSF. In the climate modeling space, BER commitment to international collaboration is more difficult to discern.

BER can promote international and collaborative leadership through a variety of mechanisms. Increasing opportunities for international scientific exchange, particularly for DOE scientists, would be valuable at all career levels, stimulating new ideas and directions

Continued on p. 135

CASE STUDY

MOSAiC—Multidisciplinary Drifting Observatory for the Study of Arctic Climate

Dramatic changes in the Arctic climate system and rapid retreat of Arctic sea ice strongly affect global climate. The inability of modern climate models to reliably reproduce Arctic climate change is one of the most pressing problems in understanding and predicting global climate change.

In 2016, the International Arctic Science Committee published the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) science plan, outlining an ambitious strategy for comprehensive new observations to decisively advance coupled-system, process-level understanding of the rapidly changing central Arctic region. Spanning the atmosphere, sea ice, and ocean, as well as physical, biological, and chemical constituents, MOSAiC was conceived from the beginning as an endeavor that would demand extensive international support and collaboration. In 2014, DOE became the first U.S. agency to commit major field resources to MOSAiC, contributing an advanced Atmospheric Radiation Measurement (ARM) mobile instrument suite to the campaign's core Central Observatory. Ultimately, more than 20 countries were involved in the 389-day expedition despite the global pandemic.

In late 2019, Polarstern, a German research icebreaker vessel, set sail from Tromsø, Norway, to spend a year drifting through the Arctic Ocean while trapped in sea ice. After launch, researchers established a distributed network of diverse instrumentation on the sea ice within about 50 km of the ship, a distance similar to a typical climate model grid box. Data was gathered continuously as the sea-ice site drifted across the polar cap toward the Atlantic Ocean. Periodic, ship-based resupply missions with partner vessels provided logistical support to more than 300 experts from 16 countries onsite during the campaign (see figure, next page).

Takeaway

The Atmospheric Radiation Measurement user facility demonstrated BER's key leadership in an international partnership by operating a major component of the largest Arctic scientific expedition in history involving more than 80 research institutions from 20 countries.

Analysis of observations commenced as soon as data began to flow, opening a second phase of international collaboration. BER's Atmospheric System Research program is funding ongoing analysis of ARM observations captured during the MOSAiC expedition. This research includes characterizing central Arctic atmospheric aerosols and clouds in unprecedented detail, quantifying the radiative balance at the sea-ice surface, and linking precipitation measurements to surface snow accumulation. To analyze atmospheric particle samples collected aboard the Polarstern, scientists will use capabilities at BER's Environmental Molecular Sciences Laboratory, specifically the state-of-the-art computer-controlled scanning electron microscope with energy dispersive X-ray spectroscopy (CCSEM-EDX). A sequencing project supported by the DOE Joint Genome Institute will provide the first annually resolved microbial inventory of the central Arctic Ocean and include data on microbial biodiversity and activity across multiple Arctic climate system interfaces sampled during MOSAiC. Crosscutting analyses will enable linkage of microbial gene functions with ecosystem processes and services such as the production of climate-active gases and primary productivity. As planned, MOSAiC's observation- and laboratory-based science is already serving as an internationally supported foundation for extensive assessment and advancement of worldwide predictive modeling tools in the Arctic region.

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CASE STUDY

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BER and the MOSAiC Expedition. **(a)** The Polarstern icebreaker carried more than 50 Atmospheric Radiation Measurement (ARM) user facility instruments for the year-long MOSAiC campaign, collecting data for comprehensively studying the central Arctic's atmosphere, ice, ocean, and ecosystem. BER's Atmospheric System Research program is helping support the ongoing data analysis. **(b)** Workers load instruments, including a radar wind profiler, onto the ship ahead of its 2019 launch in Norway. **(c)** A scientist releases a weather balloon during the expedition. **(d)** Technicians work at the Met City research station where instruments were installed on the sea ice. [All images courtesy ARM]

Continued from p. 132

that would benefit BER missions. Just as diversity within scientific teams produces different approaches to conceptualizing problems and solutions, engaging different international scientific cultures would provide new research ideas and opportunities too. Academic faculty respondents noted successes in this area related to their own experiences on sabbatical leave overseas. Furthermore, BER's international reputation and ability to attract top global talent would be enhanced by bringing foreign scientists to the United States through exchanges enabling them to work closely with DOE-funded scientists. The integration of international collaborators into DOE projects for a specified duration could benefit an entire research team.

International partnerships are common in many other countries, especially the European Union. Although some DOE programs conduct research on sensitive topics not conducive to international exchanges, BER research areas are generally free of this sensitivity. As one respondent noted, "there should be no national competition in trying to understand how Earth systems and ecosystems work." Thus, opportunities for international partnerships and collaboration may be viable and provide pathways to find new common interests, even with countries that might otherwise be considered adversaries.

Notably, the Next-Generation Ecosystem Experiments (NGEE) in the tropics and Arctic are two example projects from BER's research portfolio that could significantly leverage international cooperation to benefit DOE. NGEE Tropics is largely international, with fieldwork and data collection occurring in countries such as Brazil and Panama. Similarly, NGEE Arctic, while primarily focused in Alaska, has broad opportunities for impact and collaboration across other Arctic countries. Three additional suggestions for enhancing through partnerships the scientific leadership of BER—and more broadly the Office of Science—are described below.

1. **Develop New International Funding Programs and Establish a Formal Office for International Activities.** BER leadership could institute new mechanisms for international and cross-agency collaboration. International programs that serve as useful examples include (1) a collaboration between NSF and the United Kingdom's Natural Environment Research Council; (2) the Belmont Forum, a partnership committed to advancing transdisciplinary science for mitigating and adapting to global environmental change; (3) the U.S.-Israel Binational Science Foundation; (4) several other programs managed by the NSF Office of International Science and Engineering; and (5) NSF's Accelerating Research through International Network-to-Network Collaborations (AccelNet) program, a new initiative to "tap scientific excellence around the world and provide coordinating mechanisms to support this intellectual potential for the benefit of all."
2. **Increase Fellowships, Scholarships, and International Exchange Opportunities.** More than 60% of PhD students in science and engineering are international (Burke et al. 2022), underscoring the need to increase graduate student fellowships for U.S. students to attract them to graduate studies and postdoctoral opportunities. Expanding the scientific workforce also will require providing more opportunities for international fellowships and scholarships through international exchange. With funds provided by their respective governments, several international competitors offer extensive fellowships that enable much greater mobility of graduate students across international borders. U.S. students are at a relative disadvantage for reciprocal engagement.
3. **Optimize Resources and Efficiencies Through U.S. Agency Collaborations.** BER could achieve key partnerships and develop co-funding mechanisms for larger projects with other federal agencies that support more "blue sky" research (e.g., NSF) or have complementary resources, such as computing, field campaigns, and modeling expertise. Example cross-agency programs include the Water Sustainability and Climate project and the Innovations at the Nexus of Food, Energy, and Water Systems initiative; both of these NSF and U.S. Department of Agriculture partnerships have funded significant research over the past decade.

8.3 Enhancing Research Operations, Management, and Resources

Effective communication and expanded interactions within BER; across DOE programs; and with other federal agencies, industry, and international counterparts have the potential to change scientific cultures, expand BER's recruitment of top talent, and infuse the program with new perspectives and ideas. Other opportunities to strengthen and enhance BER's research enterprise center on successfully managing funding volatility and shifts in research program continuity and priorities. Frequent horizon scanning to identify critical and needed research opportunities and challenges will also be important.

8.3.1 Leveraging Interactions Within BER, DOE, and the Private Sector

Recent DOE organizational changes reflect federal priorities to link science and innovation more explicitly. By convening Science and Energy Technology teams that cut across the Office of Science and applied technology offices, DOE has demonstrated its commitment to open lines of communication between fundamental and applied research programs. Positive steps include proposed investment in the Energy Earthshot Research Centers and single-PI or small-team awards that range from use-inspired discovery research to technology development.

Further opportunities exist for BER to strengthen communication and interactions across its divisions and with other Office of Science programs. Many respondents noted that even basic efforts to improve coordination and communication within the Office of Science are difficult due to stove-piped offices, program-specific interpretations of mission dictates, the difficultly of establishing interagency agreements, and the implied pressure to avoid program-specific taboo topics. Effective communication has the potential to change cultures across the Office of Science, ideally creating more comfort with blue sky research and with designing use-inspired experiments and approaches for a broader set of applications.

Even within BER itself, respondents noted obvious complementary capabilities across the EESSD and BSSD research portfolios, yet co-funding and other explicit support for cross-program activities are often lacking. Environmental genomics stands out as a potential example where coordination between programs might yield fruitful outcomes. Untapped potential exists for leveraging the strengths of both divisions to generate, for example, a more accurate mechanistic understanding of the carbon cycle, from microbial to continental scales.

Some BER programmatic directives, such as efforts in Biosystems Design to promote tool development for plant and microbial synthetic biology, are directly relevant to interactions with the private sector and for the emerging bioeconomy. BER-funded discovery science underpins development of intellectual property, startups, and new industries. For example, companies such as Gingko, Zymogen, Amyris, and Millipore-Sigma take advantage of open science competitiveness in the United States.

Capabilities in synthetic biology create economic advantage but also national security vulnerabilities. The synthetic biology community has taken steps to evaluate ethical considerations in its own research. These efforts provide an interesting model for other critical research areas, such as artificial intelligence and quantum science, and their intersections with biological and environmental research, where domain expertise becomes essential for informing scientific directions when regulatory policies are lacking. As the pace of scientific discovery continues to accelerate, BER could engage more closely with DOE policy offices to consider the balance among open science, intellectual property, limitations on commercial access to data and tools, economic competitiveness, and national security.

BER proposal solicitations are typically strategic and targeted. Although successful in many ways, does this research model need to be reframed or enlarged to secure the international competitiveness of BSSD and EESSD in the 21st century? Opening the door for transformative ideas and paradigm-challenging research is in line with DOE's mission and overall strategic goals, and it offers the potential for scientific

breakthroughs and discoveries critical for addressing future environmental, economic, and energy challenges. Such a new model could strengthen ties with academia by diversifying funding mechanisms between national laboratories, academic institutions, and PIs of diverse backgrounds and career stages. Moreover, formalizing joint appointments, student exchanges, sabbaticals, and short visits could contribute to the retention of national laboratory scientists whose professional development could benefit from a dual academic-government environment.

8.3.2 Managing Funding Volatility and Program Continuity and Focus

Fluctuations in federal research appropriations and allocation of funds to specific mission-driven priorities are common across the research and development enterprise. Such fluctuations have consequences for universities; national laboratories; and the faculty, staff, and graduate students who rely on those funds. Respondents across BSSD and EESSD noted that BER's national and international leadership is vulnerable to perceived and realized uncertainties and volatility in funding, research priorities, and program continuity. Consistency in funding and strategic vision is required to maintain scientific focus, core infrastructure, and intellectual capabilities and to ensure sufficient longevity of research directions for career and workforce development.

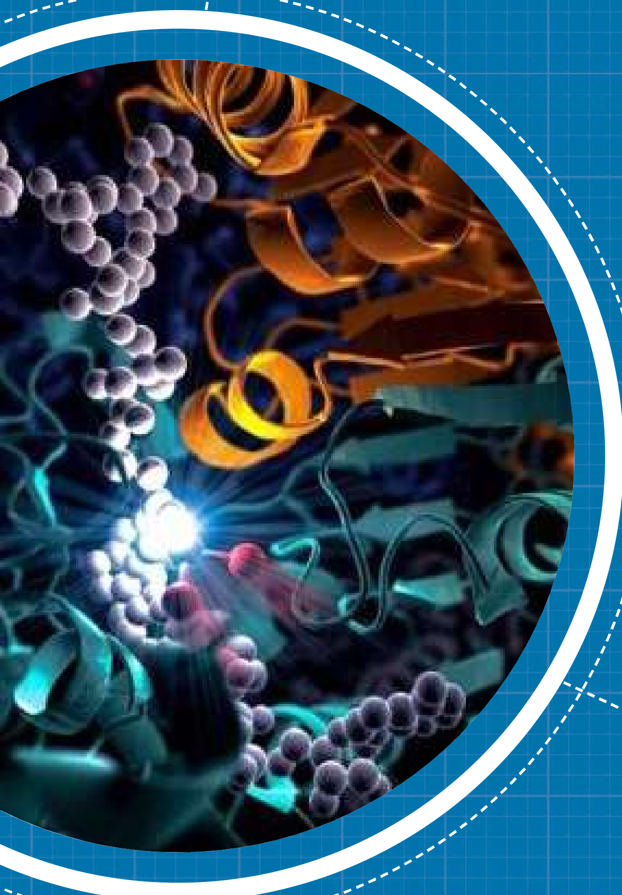
Recent rapid shifts in topical priorities and the budgetary volatility they introduce pose challenges to sustain and grow BER leadership. One artifact of these issues has been significant program manager turnover requiring the addition of new program managers and subsequent changes in perspectives, priorities, and project assignments. Because relationships with program managers and knowledge of strategic priorities are important in understanding current and future research directions, time and energy are needed to become acquainted with new personnel. The pandemic and lack of in-person annual PI meetings have complicated such endeavors recently. As part of a holistic communications strategy, BER might consider having new program managers give introductory webinars to the research community.

Although not readily apparent in annual funding cycles and budget allocations, perceived uncertainty and short-term fluctuations can impede BER science missions. Uncertainty resulting from changes of administration, presidential priorities, and changing research foci negatively impact hiring, retention, commitments to students and postdocs, and national laboratory investments. This uncertainty also reduces the willingness of scientists to fully engage in research areas no longer perceived as federal priorities and thus vulnerable to cuts. In short, the anticipation of change, whether it occurs or not, can hinder scientific commitment and progress. These perceptions and concerns are not short-lived within a given funding cycle, even if worst-case programmatic budgets are not realized; they are impacting BER's national and global reputation of supporting scientific careers and critical research for society.

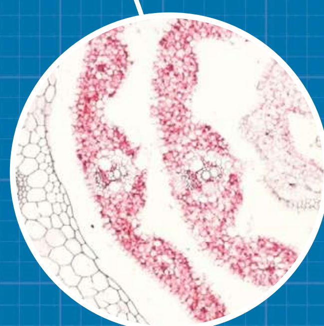
8.3.3 Horizon Scanning

BER emphasizes a research community approach in generating workshop reports and convening roundtables to identify research questions and priorities, a strategy applauded by respondents and BERAC. The program also asks the National Academies of Sciences, Engineering, and Medicine to undertake independent consensus study reports. However, as the research enterprise becomes increasingly globalized, BER needs mechanisms to increase its agility in responding to breakthrough discoveries, reconfiguring its research portfolio, and translating fundamental science to technological innovation. The program could take advantage of proven methodologies for horizon-scanning exercises and scenario planning (NASEM 2000). Also, in a global research community, science is interdependent on others for success. Thus, it is critically important that BER communicate regularly with its international counterparts.

In summary, BER science and infrastructure are world-leading in scale and scope. BER mission areas have critical roles at the nexus of global challenges related to climate change, energy transitions, and sustainable prosperity. Investment across these mission areas needs to keep pace with that of the international research community and better leverage integrative science across BER's portfolio. BER needs to frequently scan the horizon of scientific opportunities and priorities to avoid failures of inspiration and imagination.



CHAPTER 9
Reflections and Conclusions



Subcommittee Co-Chairs
Maureen McCann, *National Renewable Energy Laboratory*
Patrick Reed, *Cornell University*

9 Reflections and Conclusions

DOE's origin story is rooted in response to national needs. The agency evolved from its first iteration in 1946 as the U.S. Atomic Energy Commission, which assumed leadership of the Manhattan Project after World War II, to its 1974 reinvention during the energy crisis as the U.S. Energy Research and Development Administration, tasked with developing new energy technologies. Ultimately, in 1977, President Jimmy Carter's administration drew an equivalency between energy security and national security and formed DOE to unite these two missions under a new federal agency.

Similarly, DOE's BER program began in 1947 under a different name and has evolved since then to become an international leader in diverse fields relevant to DOE missions. In the 1950s, BER contributed to studies of chemical dispersion, atmospheric global circulation, and environmental remediation of nuclear waste. By 1987, BER had partnered with the National Institutes of Health to sequence the human genome, partly to understand the impacts of radiation on DNA but also to develop the capability to sequence any organism's genome. In the 2000s, BER responded to DOE's intention to transform the nation's energy system and secure leadership in clean energy technologies; pursue world-class science and engineering as a cornerstone of economic prosperity; and enhance nuclear security through defense, nuclear nonproliferation, and environmental efforts. Toward those goals, BER research has increased understanding of biological systems and Earth and environmental systems. Due to these efforts, BER now occupies a unique position in the global scientific funding landscape at the nexus of energy transition, climate change mitigation, and sustainable economic prosperity.

This report reflects the BERAC Subcommittee on International Benchmarking's dedication to addressing the Office of Science director's four charge questions (see charge letter, p. ii), an effort requiring 40 colleagues to commit themselves to a task encompassing more than a year of their time. From the subcommittee to the many experts who provided a wealth of input, the scientific community's engagement and enthusiasm for this effort signifies deep respect for how BER manages and operates its research enterprise to support DOE missions. On the global stage, respondents provided unequivocal evidence of BER's international leadership across its mission areas. In developing this study, the subcommittee and its colleagues became enriched by a new appreciation for BER's practices, structures, protocols, resource investment, and scientific outcomes.

Across the various mission areas, the subcommittee identified five strategic recommendations and associated risks for the next decade:

1. If our nation *fails to invest* adequately in transformative and use-inspired discovery science, it risks undermining future capabilities to mitigate climate change impacts, manage energy transitions, and promote an emerging bioeconomy enabled by recombinant DNA technology. The integration of science across BER mission space in a true systems approach is an opportunity to amplify and accelerate progress.
2. If BER and DOE *fail to capitalize on investments* in translating fundamental science to market, they risk the international competitiveness of U.S. companies in the sectors of energy, agriculture, chemicals and materials, carbon capture technologies, and associated data and services.
3. If BER and DOE *fail to imagine* the consequences of science and innovation trajectories, they risk other nations reaping the benefits of technologies that drive step changes in the global economy. As the pace of discovery accelerates across the life sciences, regular horizon scanning is critical to ensuring that BER makes informed investments in research and infrastructure to remain at the forefront.

4. If BER and DOE *fail to inspire* their stakeholders and the public, they risk diminished stature and impact at a juncture when communicating the benefits of science in addressing societal needs is critical.
5. If BER and DOE *fail to sustain future leadership* through recruitment and retention of the best and brightest in the BER mission space, they risk the nation's international leadership in biological, environmental, and Earth systems science.

Given the urgency of addressing societal grand challenges by using "Big Science" to drive solutions, failure is not an option.

Maureen McCann and Patrick Reed
Co-Chairs, BERAC Subcommittee on International Benchmarking

September 2022

Appendix A

Key Findings and Recommendations

The BERAC Subcommittee on International Benchmarking developed both overarching and science domain–specific Key Findings and Recommendations based on their work to address the DOE Office of Science charge, which entailed synthesizing responses from expert interviews, town hall participants, and a public Request For Information. Data and analyses for these findings and recommendations were gathered and developed in 2021. BER has independently acted in some cases during 2022 to address some of the issues raised.

Overarching Findings

- BER's international leadership is well-substantiated across mission areas and enabling infrastructure.
- Mission areas increasingly target the critical challenges of the coming decades for which "Big Science" can and must be entrained.
- International leadership is a more meaningful goal when viewed in a collaborative versus adversarial context.
- Future leadership is not guaranteed and will require increased investments and strategic partnerships with private, public, and academic institutions; other DOE programs; other federal agencies; international collaborators; and across disciplines.
- Volatility in priorities, funding, and workforce retention significantly threatens BER's ability to sustain its leadership.
- BER's funding over the last decade has not increased commensurately with the growing scale and acuteness of the national and global challenges that BER missions and science address.
- The science community does not widely associate BER with the major research impacts and achievements it has enabled.

Strategic Recommendations

- Increase and sustain needed resources in all mission areas and in integrative science opportunities across and between these areas (risk: failure to invest).
- Improve connection between basic science and research across Technology Readiness Levels (risk: failure to capitalize on investment).
- Establish horizon-scanning mechanisms for long-range, strategic infrastructure and mission-area investments (risk: failure of imagination).
- Elevate the stature of BER mission science to ensure recruitment of the best and brightest (risk: failure to inspire).
- Prioritize, with time and investment, a culture that supports diversity and inclusion, enables early and mid-career professional development, and delivers the future workforce (risk: failure to sustain future leadership).

Ch. 2: Bioenergy and Environmental Microbiomes

Key Findings

KF2.1 BER is an international leader in fundamental bioenergy, sustainability, and environmental microbiome research, but other countries are catching up to the United States in scientific leadership and their capacity to translate basic research into practical applications.

KF2.2 BER funding of plant science studies has positioned the United States as the world leader in plant bioenergy and feedstock research.

KF2.3 BER leads in developing and applying genome- and omics-based approaches to bioenergy and environmental microbiome research. Maintaining this position requires continued support

for new technologies and experimental testing of hypotheses generated from omics data. The next frontier will be combining multiomics approaches with innovations in microbial and plant biochemistry, areas where BER may lag other countries.

KF2.4 Several nations, including China, outperform the United States in developing and deploying technological applications, partly due to external policies and market trends, lower investment in fundamental bioprocessing research, and gaps in continuity between discovery, development, and deployment.

KF2.5 The DOE Bioenergy Research Center (BRC) program exemplifies the power of well-managed team science, which benefits from stable funding, a strong mission, and a collaboration emphasis. With well-integrated, multidisciplinary teams, the BRCs excel at performing and publishing research in foundational science and building collaborator networks, but their intellectual property has not been widely deployed.

KF2.6 Interagency calls, when initiated, provide a productive mechanism for fostering research collaborations.

Recommendations

R2.1 Spearhead a renaissance in bioenergy research, the need for which is highlighted by recent geopolitical events including the war in Ukraine and U.S. economic vulnerability to disruptions in the global energy market. To maintain its international position as a research leader, BER should support and encourage the next generation of researchers to embrace innovative, high-risk approaches for achieving bioenergy goals.

R2.2 Lead efforts to provide the fundamental knowledge needed to bring products to market. BERAC does not recommend that BER support applied research, since BER's strength and preeminence lie in fundamental science. However, BER should engage in creative opportunities to catalyze communication between basic and applied researchers to speed transitions between early Technology Readiness Levels.

R2.3 Encourage interactions and interdisciplinary collaborations that better integrate the unique architecture of BER's research portfolio and provide the research community with access to established resources such as ongoing perennial field experiments and their growing data collections. These activities will generate knowledge between and across disciplines and experimental scales, from computation to experimentation and from molecules to phenotypes.

R2.4 Build on genome-enabled bioenergy and environmental microbiome leadership and knowledge to understand the complex interactions between bioenergy crops and environmental microbiomes, thereby informing sustainable management of ecosystems under climate change.

Ch. 3: Biosystems Design

Key Findings

KF3.1 The relatively recent launch of BER's Biosystems Design research program is already yielding high-profile research accomplishments.

KF3.2 BER holds a strong leadership position in microbial biodesign, particularly in bacterial systems. However, leadership is increasingly distributed across the globe, with the United States considered "one of many" leaders for yeast and other fungi.

KF3.3 BER does not lead in understanding microbial physiology during bioprocess scale-up.

KF3.4 No world region yet leads in plant biodesign, suggesting that BER could target investments to yield substantial intellectual returns.

Recommendations

R3.1 Establish new Biodesign Research Centers patterned off existing DOE Bioenergy Research Centers to leverage advancements in BER's

Biosystems Design research, which encompasses multiple applications and could potentially synergize various biological platforms, including nonmodel and photosynthetic microbes.

R3.2 Explore and coordinate joint funding calls with international agencies to accelerate progress in biodesign by leveraging key expertise from other countries.

R3.3 Encourage replication of recent machine-learning breakthroughs, such as AlphaFold 2.0, and development of new deep-learning algorithms more broadly in biodesign. Target funding for curating, mining, and generating omics datasets and developing laboratory automation tools for generating high-quality datasets to train machine-learning models that support biodesign.

R3.4 Invest in disruptive, bold initiatives to accelerate plant synthetic biology and plant transformation processes in coordination with the National Science Foundation and other agencies.

R3.5 Expand support for biomanufacturing training programs for doctorate and nondoctorate workforces that critically feed the talent pipeline for the U.S. biotechnology industry.

Ch. 4: Environmental System Science

Key Findings

KF4.1 BER's Environmental System Science (ESS) research program is highly cited and internationally respected for its:

a. Multidisciplinary systems science.

b. ModEx (modeling-experimental) approach that emphasizes an iterative exchange of knowledge and discovery among predictive models, experiments, and observational field research, leading to novel discoveries.

c. Research infrastructure, including large-scale ecosystem manipulations such as the Spruce and Peatland Responses Under Changing Environments (SPRUCE) project, AmeriFlux, and watershed Science Focus Areas, which support cross-agency and international collaboration.

d. Terrestrial Ecology research, including biogeochemistry, ecosystem fluxes, and climate change responses.

e. Watershed Sciences research, including multiscale hydro-biogeochemical modeling and process studies.

KF4.2 ESS research has untapped potential for:

a. Better integrating human influence into the study of natural systems.

b. Supporting both creative discovery science and the translation of research to inform applied solutions.

c. Bridging the gaps between terrestrial sciences and atmospheric and climate sciences.

Recommendations

R4.1 Embrace coupled human-natural systems as a critical niche for ESS contributions in the next decade while maintaining the focus on mechanisms and process understanding.

R4.2 Elevate and integrate tools for data discovery and analysis at a level commensurate with ESS data volume and complexity to accelerate scientific impact.

R4.3 Facilitate the translation of ESS research into solutions and innovations by the DOE offices with a mandate for applied work and other potential partners.

R4.4 Create avenues for the research community to communicate and interact across the DOE science and technology pipeline, leading to breakthroughs, greater inclusivity, improved efficiencies, and reduced time lags between needs assessment, fundamental science, and application.

R4.5 Become an international leader in providing safe and inclusive fieldwork by building on existing ESS accomplishments, developing and sharing ESS resources, and modeling the successes that arise from equitable professional environments.

R4.6 Maintain global leadership in large-scale ecosystem manipulation experiments, a hallmark of BER science, which integrate ESS domains, promote ModEx, and foster collaboration among domestic and international institutions.

R4.7 Ensure that ESS strategic priority and funding paradigms support foundational research opportunities to continue international domain leadership.

Ch. 5: Climate Science

Key Findings

KF5.1 BER-funded climate science publications are among the most highly cited papers in the field, garnering a higher rate of citations than non-BER publications, particularly for the top 1% and 5% of papers.

KF5.2 BER has demonstrated international leadership in developing and interpreting climate model intercomparisons through the DOE Program for Climate Model Diagnosis and Intercomparison (PCMDI) and was a leading contributor to research earning the 2007 Nobel Peace Prize awarded to the Intergovernmental Panel on Climate Change and former U.S. Vice President Al Gore.

KF5.3 BER is a world leader in climate change and cloud feedback research through its application of the "fingerprint" method to identify signatures of human influence on climate and its development of innovative techniques to quantify cloud feedbacks and pin down equilibrium climate sensitivity.

KF5.4 BER has advanced exascale computing to become one of the world's leading developers of kilometer-scale Earth system models, such as the convection-permitting Energy Exascale Earth System Model.

KF5.5 BER has successfully developed capabilities in crosscutting energy-related research and coupled human-Earth system models, such as the Global Change Analysis Model.

KF5.6 BER leads internationally in capturing ground-based and aerial atmospheric measurements through its Atmospheric Radiation Measurement (ARM) user facility and in advancing physical understanding of atmospheric systems through the associated Atmospheric System Research program.

Recommendations

R5.1 Increase investment in development of kilometer-scale Earth system modeling by advancing exascale computing, artificial intelligence and machine-learning approaches, and model-observation integration.

R5.2 Strengthen international leadership in modeling the coupled human-Earth system by providing more decision-relevant insights and better accounting for model uncertainties.

R5.3 Sustain international leadership in ground-based and aerial measurements and their use in advancing physical process understanding by strengthening collaborations with the satellite community, supporting integration of national and international field-observing systems, and potentially establishing synergistic leadership in laboratory chamber facilities.

R5.4 Strengthen international leadership in model intercomparison activities and in climate sensitivity research by increasing support for PCMDI, the Earth System Grid Federation, and process-oriented exercises that use ARM observations.

R5.5 Establish sustained and substantial funding for expanded collaboration between U.S. agencies and universities to improve research outcomes and integration of efforts to meet societal needs.

R5.6 Create additional means for supporting "blue sky" proposals from DOE scientists to stimulate innovation and workforce engagement.

Ch. 6: Enabling Infrastructure

Key Finding

KF6.1 The review showed that BER research is currently supported by six world-class infrastructure capabilities:

a. **DOE Joint Genome Institute (JGI).** BER's JGI is the world's largest center for nonbiomedical genomic science research, supporting DOE missions in clean energy and environmental characterization and cleanup. It provides integrated high-throughput sequencing and computational analysis that enable systems-based approaches to these challenges.

b. **Atmospheric Radiation Measurement (ARM) User Facility.** BER's ARM is internationally recognized for its long-term ground-based observation facilities, which have been advancing global atmospheric and climate research for 40 years. ARM's long-term data records, breadth of conditions and locations over diverse climate-relevant areas, and influence in the study of the climate system are unmatched by any other ground-based programs around the world.

c. **AmeriFlux and the AmeriFlux Management Project.** BER-supported AmeriFlux is a collection of long-term, eddy flux stations that measure ecosystem carbon, water, and energy fluxes across the Americas. One of two leading global flux networks, AmeriFlux is part of the international FLUXNET project and has taken the lead in creating the FLUXNET synthesis data products, the most impactful international observational product.

d. **National Synchrotron Light Source II (NSLS-II).** Supported by DOE's Office of Basic Energy Sciences, NSLS-II is the newest and most advanced synchrotron in the United States. The facility's design optimizes the creation of tightly collimated, high-flux light beams, covering the spectral range from infrared to high-energy X-rays. This unique combination of performance characteristics has allowed the creation of world-leading instruments, such as imaging with high spatial resolution (~10 nm) and chemical sensitivity, opening up novel possibilities for the study of biological material dynamics. Additional BER co-funded instruments with small beams (1 μm) are enabling high-resolution structural information from tiny protein crystals.

e. **DOE Leadership Computing Facilities.** Supported by DOE's Advanced Scientific Computing Research program, the Argonne Leadership Computing Facility, Oak Ridge Leadership Computing Facility (OLCF), and National Energy Research Scientific Computing Center are critical parts of the enabling infrastructure on which BER scientists rely. In June 2022, the high-performance computing community's international benchmarking effort ranked OLCF's Frontier supercomputer as the fastest in the world after it became the first system to break the exascale barrier. What distinguishes these DOE systems from international comparators is the science support ecosystem around them, provided by the DOE Exascale Computing Project (ECP). BER science has benefited from ECP in both its climate (Energy Exascale Earth System Model) and biology (ExaBiome) research.

f. **Environmental Molecular Sciences Laboratory.** EMSL delivers leading facilities, advanced instrumentation, and scientific leadership that empower and enable a national and international community of researchers to advance BER's mission to achieve a

predictive understanding of complex biological, Earth, and environmental systems.

Recommendations

R6.1 Establish an oversight board to assess strategic decisions about creating, continuing, and sunsetting all BER infrastructure capabilities. This board should develop and publish a regularly updated 5- to 10-year strategic roadmap for infrastructure capabilities that support mission-critical science, coordinating with other DOE offices and national and international agencies to maximize investment and impact.

R6.2 Promote greater integration across user facilities—including harmonization of data management and analysis services—to enable researchers to easily schedule and use different infrastructure capabilities.

R6.3 Consider creating data user facilities and providing long-term support for their governance, planning, policy development, and technological needs.

R6.4 Establish a cross-facility working group to develop and share a foundational BER data policy and best practices for data use, licensing, and citation.

R6.5 Increase computational and storage capacity for BER researchers.

Ch. 7: Integrative Science

Key Findings

KF7.1 BER leads internationally in integrating climate observations and modeling, and its Atmospheric Radiation Measurement (ARM) user facility and Atmospheric System Research (ASR) program are international leaders of integrative science involving short-term field campaigns.

KF7.2 Sustaining leadership in the integration of the ARM, ASR, and Earth system modeling programs requires both maintenance of cutting-edge observational capabilities and continued access to adequate computational resources.

KF7.3 Additional leadership gains would be achieved by improving integration across the Energy Exascale Earth System Model (E3SM), the Program for Climate Model Diagnosis and Intercomparison, research in Regional and Global Model Analysis, ARM, and MultiSector Dynamics modeling efforts.

KF7.4 The DOE Bioenergy Research Centers (BRCs) exemplify interdisciplinary research ranging from detailed molecular analysis to ecosystem modeling.

KF7.5 DOE's Environmental Molecular Sciences Laboratory (EMSL), Joint Genome Institute (JGI), and light source user facilities, along with their numerous collaborators, are international leaders in integrating omics research, molecular and structural analysis, and systems biology.

KF7.6 BER is a leader in systems-level understanding such as the linkages between plant microbiomes and ecosystem function.

KF7.7 EMSL successfully integrates atmospheric science and physical chemistry with potential expansion into biological aerosols.

KF7.8 Citation analysis demonstrates integration success: BER-sponsored papers are 1.5 times more likely than non-BER papers to span two BER science areas and 3 times more likely to span three.

KF7.9 BER research could be further integrated by developing opportunities embodied in crosscutting user facility programs such as the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) project and the Facilities Integrating Collaborations for User Science (FICUS) initiative.

KF7.10 Integrating efforts across U.S. agencies is a formidable challenge leaving unrealized opportunities for further integration across BER's portfolio.

Recommendations

R7.1 Improve BER's capacity for integrative research within and beyond its research portfolio.

a. Solicit support from the National Academies

of Sciences, Engineering, and Medicine for synthesizing capabilities, needs, and opportunities across BER-relevant user facilities and field sites funded by DOE and other U.S. agencies to accelerate groundbreaking integrative research.

b. Create sustained funding opportunities across BER, DOE, and other agencies (where possible) to advance a more integrated understanding of biological and environmental systems at multiple scales.

c. Strengthen workforce capacity for integration by better supporting integrative research with targeted funding opportunities, particularly among early career researchers.

R7.2 Advance a more complete understanding of coupled human-natural systems in BER science areas.

a. Include coupled human-natural system dynamics in BER funding opportunities.

b. Launch a multiagency research program to improve integration across both the MultiSector Dynamics and Earth and Environmental Systems Modeling programs.

c. Establish research sites for integrated long-term studies that span genomes to landscapes and the subsurface to atmosphere.

R7.3 Build international collaborations to strengthen BER's global leadership in the genomic, environmental, and climate modeling sciences.

a. Work jointly with other U.S. agencies to develop an internationally coordinated effort that will provide public and private stakeholders with urgently needed climate and environmental data.

b. Explore the potential for coordinating and promoting international collaborations that would leverage BER's investments in the genomic and environmental sciences, including the BRCs.

R7.4 Support integration through existing and new user facilities.

a. Establish a computational synthesis center to support the pursuit of questions that demand targeted integration across disciplines and scales.

b. Dedicate a cross-facilities operational budget to fund integrative science projects spanning multiple BER user facilities.

Ch. 8: Strategies for People, Partnerships, and Productivity

Key Findings

PEOPLE

KF8.1 BER funds academic scientists across the nation who contribute exceptional talent and new expertise to the program's mission.

KF8.2 The DOE national laboratory complex provides many positive career opportunities for BER-funded scientists.

KF8.3 Programs for undergraduates, graduate students, and postdoctoral students effectively recruit scientific talent for BER missions.

KF8.4 The lack of workforce diversity significantly limits BER's long-term leadership and the necessary growth of its scientific workforce.

KF8.5 BER frontier research successes and impacts lack visibility.

KF8.6 BER funding for high-risk discovery science and paths to independent work are rare at the national laboratories, and increased funding flexibility is desired at all career levels.

KF8.7 Real and perceived volatility in funding levels and research topics hampers workforce recruitment and retention at all career stages and impedes long-term productivity.

KF8.8 Current funding models produce high levels of professional anxiety among national laboratory programmatic staff who feel pressure to continuously secure projects that support their own salaries.

KF8.9 At some user facilities, limited opportunities exist for support staff advancement, independent research, and future career choices, leading to overwork and professional burnout. These challenges vary significantly depending on the operational model of a given facility.

KF8.10 Over the last decade, BER has seen attrition of scientific workforce talent, particularly among academic Early Career Research Program awardees, half of whom are no longer funded in the BER mission space.

KF8.11 Some BER-supported Early Career awards are limiting workforce development due to their timing and topical volatility, providing only narrow windows of opportunity in a scientist's career pathway. This impact is more pronounced for the Earth and Environmental Systems Sciences Division than the Biological Systems Science Division and its more stable approach.

PARTNERSHIPS

KF8.12 Although international collaborations are critical for strengthening BER scientific output and increasing global visibility, such partnerships are difficult for BER-funded institutions due to funding restrictions between countries.

KF8.13 BER program staff and BER-supported scientists have few resources to travel or engage internationally.

KF8.14 Meeting societal needs requires more domestic and international collaborations for ground-based observations and high-resolution Earth system modeling to improve research outcomes and ensure integration of efforts.

KF8.15 Because of its mobile facilities and ability to fund international partners, the Atmospheric Radiation Measurement (ARM) user facility excels in collaborations—both in the United States and abroad.

PRODUCTIVITY

KF8.16 BER user facilities are specially positioned to integrate researchers across BER because of their unique expertise, leadership positions, and ability to attract users.

KF8.17 The Bioenergy Research Center (BRC) program achieves strategically important BER mission goals, and its model could be applied to other relevant research areas, such as environmental microbiomes. With their integrative focus, the BRCs have excelled at building impactful and highly productive researcher networks working toward a common goal.

KF8.18 BER should maintain team-based projects combining researchers from academic institutions and DOE national laboratories.

KF8.19 Silos and mission boundaries within DOE and across agencies block the potential for science accomplishments to inform innovation and applied solutions.

KF8.20 U.S. agencies should consider opportunities to expand collaborative climate science research beyond the current facilitating role of the U.S. Global Change Research Program, which lacks allocated funding.

Recommendations

PEOPLE

R8.1 Incentivize efforts to increase workforce diversity and provide a culture of inclusivity, explicitly measuring successes and evaluating outcomes continually for further improvements using processes with broad participation.

R8.2 Invest in effectively communicating BER scientific successes and proactively convey the importance of the program's research mission to better recruit and retain top global talent.

R8.3 Support Early Career award researchers in their future and post-award career paths by providing training and opportunities for research leadership.

R8.4 Provide incentives to the national laboratories for creating and sustaining professional development opportunities for early and mid-career scientists.

R8.5 Develop and demonstrate balanced models for providing BER-supported researchers with options for both collaborative teaming paths and individual successes.

PARTNERSHIPS

R8.6 Enhance international partnerships and cross-agency cooperation by developing new funding modalities, such as joint calls with the National Science Foundation and other agencies.

R8.7 Increase opportunities for BER program managers and supported scientists to engage with their international counterparts.

R8.8 Develop new international programs and consider establishing a formal office for international activities.

R8.9 Increase fellowships, scholarships, and international exchange opportunities.

R8.10 Optimize resources and efficiencies by bridging across agencies and nations.

PRODUCTIVITY

R8.11 Promote more effectively BER's world-class programs; unique facilities; and leadership in creating synergies across observations, process studies, and system modeling.

R8.12 Secure leadership in both the science areas where BER already excels (e.g., observation and modeling integration) and in new growth areas.

R8.13 Assign facilities the responsibility of coordinating and storing the data relevant to their main area of expertise.

R8.14 Increase emphasis in modeling activities related to uncertainty quantification and uncertainty propagation for complex, multiscale systems.

R8.15 Build a productive, creative workforce by supporting interdisciplinary research opportunities for early and mid-career scientists, as is done by crosscutting organizations such as the Max Planck Institutes in Europe or Chinese institutes for environmental and climate science.

R8.16 Manage volatility, potential and realized, in funding levels and award topics.

R8.17 Use inter- and intra-agency cooperation and co-funding to foster interdisciplinary collaborations, maximize large-scale resources, and bridge Technology Readiness Levels (TRLs).

R8.18 Create a culture of communication and interaction across the TRL spectrum in DOE and among BER, businesses, and nongovernmental organizations.

R8.19 Develop integrative science opportunities as a signature area for BER.

Appendix B

BERAC Members

Chair

Bruce Hungate, *Northern Arizona University*

Members

Caroline Ajo-Franklin, *Rice University*
Cris Argueso, *Colorado State University*
Sarah M. Assmann, *Pennsylvania State University*
Ana P. Barros, *University of Illinois*
Bruno Basso, *Michigan State University*
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Sen Chiao, *Howard University*
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Jorge E. Gonzalez-Cruz, *City College of New York*
Ramon Gonzalez, *University of South Florida*
Randi Johnson, *Formerly U.S. Department of Agriculture*
Kerstin Kleese van Dam, *Brookhaven National Laboratory*
Sonia Kreidenweis, *Colorado State University*
Maureen McCann, *National Renewable Energy Laboratory*
Xiaohong Liu, *Texas A&M University*
Gerald A. Meehl, *National Center for Atmospheric Research*
Gloria K. Muday, *Wake Forest University*
Dev Niyogi, *Jackson School of Geosciences*
Himadri Pakrasi, *Washington University in St. Louis*
Kristala Prather, *Massachusetts Institute of Technology*
Patrick Reed, *Cornell University*
Gemma Reguera, *Michigan State University*
Jeremy Schmutz, *Hudson Alpha Institute for Biotechnology*
Daniel Segrè, *Boston University*
Karen Seto, *Yale University*
Matthew D. Shupe, *University of Colorado and NOAA*
Huimin Zhao, *University of Illinois at Urbana-Champaign*

Appendix C
Approach to Metrics and Methodologies

We are deeply grateful to Tristram West, our guide within this report and to BER; to AAAS fellow Wayne Kontur, on detail at BER; and to Mary Beth West and Joshua Nelson from DOE's Office of Scientific and Technical Information.

Methodology for Publication and Citation Analysis

The BERAC subcommittee performed a quantitative assessment of BER-focused research, resulting publications, and citation metrics to assess the relative impact of BER-sponsored research. This quantitative research analyzed publications and citations from Clarivate's Web of Science (WoS) Expanded Application Programming Interface (API). WoS is an independent global citation database with almost 1.9 billion cited references from over 171 million records.

Bibliometric analysis is one method to determine the relative impact of a publication. For this research, the BERAC subcommittee assessed the citation activity of relevant publications to compare BER-related research. Similar reporting activities[1] have used citation-based bibliometrics to support scientific and scholarly comparisons.

For this study, the evaluation dataset was composed of journal articles published between 2010 and 2020. The final queries were pulled from the WoS Expanded API in mid-March 2022.

Comparison groups (e.g., BER, U.S./domestic, and non-U.S./international) were identified via funding information and author affiliations as follows:

- **BER:** If a publication's funding agency, funding details, or funding text fields contain "BER," "Biological and Environmental Research," or "Biological and Environmental Research," a publication is considered to be in the BER comparison group.
- **U.S./domestic:** If a publication's authorship contains U.S. affiliations, a publication is considered to be in the U.S. comparison group. This is consistent with how country facets are identified in WoS front-end search analyses.
- **Non-U.S./international:** If a publication falls into neither of the first two categories, it is considered to be in the non-U.S. comparison group.

The subcommittee scoped and iterated through a three-phase data aggregation and analysis approach to support quantitative comparisons of BER-sponsored research compared to domestically and internationally funded research. To characterize the research areas, each working group identified relevant domain-specific subjects and keywords that represent BER research and could be applied to assess domestic and international research. WoS API queries were developed using each working group's keywords.

Phase One Methodology

For the first research phase, the subcommittee identified suitable comparison metrics, identified BER's Science Focus Areas[2] (SFAs) as a method to derive initial subject areas, and developed a method for acquiring and analyzing the publication and citation metadata.

Development of the initial set of BER SFA-focused WoS queries involved combinations of manual and automated keyword lists. These WoS queries were used to perform an exploratory assessment of relevant publications, inform the scoping of future phases, and provide preliminary comparative metrics using "average citation per publication" as a baseline metric.

BER's SFAs were used to characterize distinct areas of research for comparison purposes, which were later grouped into discrete concepts. For each SFA, high-level keywords were compiled based on a manual

[1] science.osti.gov/-/media/bes/pdf/reports/2021/International_Benchmarking-Report.pdf

[2] science.osti.gov/ber/Funding-Opportunities/L y-Scientific-Focus-Area-Guidance

review of past funding opportunity announcements[3] (FOAs). Additional keywords were aggregated through comparison activities, during which SFA text descriptions were compared to publications in Microsoft Academic Graph[4].

Using a Gensim/Doc2Vec model, which was trained on more than 80 million English language publications, each SFA description was associated with Microsoft Knowledge Graph[5] (MKG) knowledge labels from domain-relevant publications. These sets of knowledge labels were further curated by subject matter experts in each working group and used to further expand and adjust the Phase One WoS queries.

Phase Two Methodology

The BERAC subcommittee reviewed the generated Phase One WoS queries, the aggregated publication lists, and the resulting metrics to inform Phase Two's quantitative evaluation.

In the first phase, BER SFAs were used to delineate concept areas for exploratory query development and comparison. In the second phase, concept areas were realigned around the working group research areas; this shift more directly aligned with this report's charge letter. The exploratory SFA queries were mapped to working groups where appropriate and, along with additional feedback from working groups in Phase One, were used as a basis for acquiring an initial publication dataset.

Author-supplied keywords and WoS subject labels were extracted from metadata in the initial dataset to identify additional concept labels characterizing working group research areas. Metadata was also matched against Microsoft Academic data to identify other relevant MKG labels. Aggregated term lists were provided to working groups for review and keyword gap analysis. Refined queries were developed with feedback from each working group, and these queries were used to pull a preliminary dataset for analysis, 2010–2020 inclusive, using the WoS Expanded API.

After comparing and aggregating available knowledge labels, a keyword gap analysis was performed, and the analysis was sent to each relevant working group. Each working group reviewed the analysis, and the keywords were refined into the appropriate WoS API queries, which were again reviewed by each working group.

Publications in the analysis dataset were separated into funding comparison groups (i.e., BER, U.S/domestic, and non-U.S./international) by referencing each publication's funding acknowledgments and author affiliations, as described above. Citation numbers were used to calculate benchmark metrics of representation in top citation percentiles and average citations per publication over the reporting period.

At the end of Phase Two, the WoS queries, all extracted publication metadata, and the aggregated results (e.g., comparative citation benchmark and analysis) were reviewed by each working group. Each working group performed data validation and analysis, which resulted in additional feedback to inform Phase Three query iteration and refinement.

Phase Three Methodology

During the last phase of quantitative data acquisition and analysis, the WoS queries were finalized, and this study's publications dataset was pulled from the WoS API in mid-March 2022.

To finalize the queries, each working group reviewed the Phase Two dataset (e.g., relevant WoS queries, citation analysis, etc.). Phase Two publication metadata were reviewed and compared against known BER, domestic, and international publication lists to identify gaps in concept coverage. To address coverage gaps, additional datasets associated with specific programs in funding acknowledgment or funding opportunities were also pulled and used for this purpose.

Finalized WoS queries to support benchmark metrics were reviewed and approved by the working groups. After the queries, the benchmark metric datasets were pulled and analyzed to compile final results.

Additional datasets and results beyond benchmark metrics were developed and provided on an as-needed basis in response to individual working

[3] science.osti.gov/ber/Funding-Opportunities

[4] www.microsoft.com/en-us/research/project/microsoft-academic-graph/

[5] makg.org

group requests. These additional queries were developed for deeper analyses supporting specific narrative elements. In some cases, these analyses do not fall within the scope of this report but may inform later inquiries.

Chapter 6 Metrics

- Number of user groups and users
- Acknowledgments of use of the facility in publications
- Use of international facilities by BER researchers and vice versa
- For light and neutron sources, and cryo-EM facilities—number of Protein Data Bank deposits
- Development of new capabilities
- Facility utilization and level of subscription
- Outreach and dissemination metrics.

Chapter 7 Metrics

- Integrative science occurs in multiple dimensions—lab/fieldwork/modeling/theory within an area of research or across different areas of science
- Survey among leaders of integrative research activities
- Interdisciplinarity (multiple programs, multi-agency) of high-impact publications
- Synergistic collaborations across U.S. agencies and entities (numbers of projects)
- Mechanisms that allow national laboratories to collaborate

Final Web of Science Queries (Phase Three)

Working Group 2 Keyword Queries

"biosynthetic pathway*" or "metabolic engineering" or "synthetic biology" or (("metabolic engineering" or "metabolic modeling" or "metabolic network" or "secondary metabolism") and (bacteria or microbe*)) or (("metabolic engineering" or "metabolic modeling" or "metabolic network" or "secondary metabolism") and "systems biology") or (("metabolic engineering" or "metabolic modeling" or "metabolic network" or "secondary metabolism") and ("biosynthetic pathway*" or "pathway engineering")) or (("metabolic engineering" or "metabolic modeling" or "metabolic network" or "secondary metabolism") and (biofuel* or bioproduct* or biomaterial*)) or (("metabolic engineering" or "metabolic modeling" or "metabolic network" or "secondary metabolism") and ("genome engineering" or "genome-scale engineering" or "genome scale model*")) or (("metabolic engineering" or "metabolic modeling" or "metabolic network" or "secondary metabolism") and "microbiome engineering") or (("metabolic engineering" or "metabolic modeling" or "metabolic network" or "secondary metabolism") and ("adaptive laboratory evolution" or "directed evolution" or "rational design")) or (("metabolic engineering" or "metabolic modeling" or "metabolic network" or "secondary metabolism") and ("computational protein design" or "protein engineering" or "protein design" or "enzyme engineering")) or (("metabolic engineering" or "metabolic modeling" or "metabolic network" or "secondary metabolism") and ("artificial intelligence" or "machine learning" or "multiscale model*" or "multi-scale model*")) or (("metabolic engineering" or "metabolic modeling" or "metabolic network" or "secondary metabolism") and ("data exchange standard*" or "data infrastructure" or "data ontolog*")) or ((bacteria or microbe*) and "systems biology") or ((bacteria or microbe*) and ("biosynthetic pathway*" or "pathway engineering")) or ((bacteria or microbe*) and (biofuel* or bioproduct* or biomaterial*)) or ((bacteria or microbe*) and ("genome engineering" or "genome-scale engineering" or "genome scale model*")) or ((bacteria or microbe*) and "microbiome engineering") or ((bacteria or microbe*) and ("adaptive laboratory evolution" or "directed evolution" or "rational design")) or ((bacteria or microbe*) and ("computational protein design" or "protein engineering" or "protein design" or "enzyme engineering")) or ((bacteria or microbe*) and ("artificial intelligence" or "machine learning" or "multiscale model*" or "multi-scale model*")) or ((bacteria or microbe*) and ("data exchange standard*" or "data infrastructure" or "data ontolog*")) or ("systems biology" and ("biosynthetic pathway*" or "pathway engineering")) or ("systems biology" and (biofuel* or bioproduct* or biomaterial*)) or ("systems biology" and ("genome engineering" or "genome-scale engineering" or "genome scale model*")) or ("systems biology" and "microbiome engineering") or ("systems biology" and ("adaptive laboratory evolution" or "directed evolution" or "rational design")) or ("systems biology" and ("computational protein design" or "protein engineering" or "protein design" or "enzyme engineering")) or ("systems biology" and ("artificial intelligence" or "machine learning" or "multiscale model*" or "multi-scale model*")) or ("systems biology" and ("data exchange standard*" or "data infrastructure" or "data ontolog*")) or (("biosynthetic pathway*" or "pathway engineering") and (biofuel* or bioproduct* or biomaterial*)) or (("biosynthetic pathway*" or "pathway engineering") and ("genome engineering" or "genome-scale engineering" or "genome scale model*")) or (("biosynthetic pathway*" or "pathway engineering") and "microbiome engineering") or (("biosynthetic pathway*" or "pathway engineering") and ("adaptive laboratory evolution" or "directed evolution" or "rational design")) or (("biosynthetic pathway*" or "pathway engineering") and ("computational protein design" or "protein engineering" or "protein design" or "enzyme engineering")) or (("biosynthetic pathway*" or "pathway engineering") and ("artificial intelligence" or "machine learning" or "multiscale model*" or "multi-scale model*")) or (("biosynthetic pathway*" or "pathway engineering") and ("data exchange standard*" or "data infrastructure" or "data ontolog*")) or ((biofuel* or bioproduct* or biomaterial*) and ("genome engineering" or "genome-scale engineering" or "genome scale model*")) or ((biofuel* or bioproduct* or biomaterial*) and "microbiome engineering") or ((biofuel* or bioproduct* or biomaterial*) and ("adaptive laboratory evolution" or "directed evolution" or "rational design")) or ((biofuel* or bioproduct* or biomaterial*) and ("computational protein design" or "protein engineering" or "protein design" or "enzyme engineering")) or ((biofuel* or bioproduct* or biomaterial*) and ("artificial intelligence" or "machine learning" or "multiscale model*" or "multi-scale model*")) or ((biofuel* or bioproduct* or biomaterial*) and ("data exchange standard*" or "data infrastructure" or "data ontolog*")) or (("genome engineering" or "genome-scale engineering" or "genome scale model*") and "microbiome engineering") or (("genome engineering" or "genome-scale engineering" or "genome scale model*") and ("adaptive laboratory evolution" or "directed evolution" or "rational design")) or (("genome engineering" or "genome-scale engineering" or "genome scale model*") and ("computational protein design" or "protein engineering" or "protein design" or "enzyme engineering")) or (("genome engineering" or "genome-scale engineering" or "genome scale model*") and ("artificial intelligence" or "machine learning" or "multiscale model*" or "multi-scale model*")) or (("genome engineering" or "genome-scale engineering" or "genome scale model*") and ("data exchange standard*" or "data infrastructure" or "data ontolog*")) or ("microbiome engineering" and ("adaptive laboratory evolution" or "directed evolution" or "rational design")) or ("microbiome engineering" and ("computational protein design" or "protein engineering" or "protein design" or "enzyme engineering")) or ("microbiome engineering" and ("artificial intelligence" or "machine learning" or "multiscale model*" or "multi-scale model*")) or ("microbiome engineering" and ("data exchange standard*" or "data infrastructure" or "data ontolog*")) or (("adaptive laboratory evolution" or "directed evolution" or "rational design") and ("computational protein design" or "protein engineering" or

"protein design" or "enzyme engineering")) or (("adaptive laboratory evolution" or "directed evolution" or "rational design") and ("artificial intelligence" or "machine learning" or "multiscale model*" or "multi-scale model*")) or (("adaptive laboratory evolution" or "directed evolution" or "rational design") and ("data exchange standard*" or "data infrastructure" or "data ontolog*")) or (("computational protein design" or "protein engineering" or "protein design" or "enzyme engineering") and ("artificial intelligence" or "machine learning" or "multiscale model*" or "multi-scale model*")) or (("computational protein design" or "protein engineering" or "protein design" or "enzyme engineering") and ("data exchange standard*" or "data infrastructure" or "data ontolog*"))

Working Group 2 Funding Queries

BER or "Biological and Environmental Research" or "Biological & Environmental Research"

Working Group 3 Keyword Queries

(biomass or biofuel* or bioenergy or feedstock or ethanol) and (biorefinery or "metabolic engineering" or "synthetic biology" or *cellulos* or lignin or switchgrass or "corn stover" or arabidopsis or "enzymatic hydrolysis" or fermentation or genom* or genom* or "systems biology" or *omics or plant or microb*)

Working Group 3 Funding Queries

BER or "Biological and Environmental Research" or "Biological & Environmental Research"

Working Group 4 Keyword Queries

("environmental system*" and ecolog*) or ("environmental system*" and ecosystem*) or ("environmental system*" and hydrolog*) or ("environmental system*" and ("soil water" or "surface water" or watershed*)) or ("environmental system*" and "terrestrial ecosystem*") or ("environmental system*" and (biogeochem* or biogeophys* or hydrobiogeochem* or "microbial community")) or ("environmental system*" and subsurface) or ("environmental system*" and soil) or (ecolog* and ecosystem*) or (ecolog* and hydrolog*) or (ecolog* and ("soil water" or "surface water" or watershed*)) or (ecolog* and "terrestrial ecosystem*")or (ecolog* and (biogeochem* or biogeophys* or hydrobiogeochem* or "microbial community")) or (ecolog* and subsurface) or (ecolog* and soil) or (ecosystem* and hydrolog*) or (ecosystem* and ("soil water" or "surface water" or watershed*)) or (ecosystem* and "terrestrial ecosystem*") or (ecosystem* and (biogeochem* or biogeophys* or hydrobiogeochem* or "microbial community")) or (ecosystem* and subsurface) or (ecosystem* and soil) or (hydrolog* and ("soil water" or "surface water" or watershed*)) or (hydrolog* and "terrestrial ecosystem*") or (hydrolog* and (biogeochem* or biogeophys* or hydrobiogeochem* or "microbial community")) or (hydrolog* and subsurface) or (hydrolog* and soil) or (("soil water" or "surface water" or watershed*) and "terrestrial ecosystem*") or (("soil water" or "surface water" or watershed*) and (biogeochem* or biogeophys* orhydrobiogeochem* or "microbial community")) or (("soil water" or "surface water" or watershed*) and subsurface) or (("soilwater" or "surface water" or watershed*) and soil) or ("terrestrial ecosystem*" and (biogeochem* or biogeophys* or hydrobiogeochem* or "microbial community")) or ("terrestrial ecosystem*" and subsurface) or ("terrestrial ecosystem*" and soil) or((biogeochem* or biogeophys* or hydrobiogeochem* or "microbial community") and subsurface) or ((biogeochem* or biogeophys*or hydrobiogeochem* or "microbial community") and soil)

Working Group 4 Funding Queries

BER or "Biological and Environmental Research" or "Biological & Environmental Research"

Working Group 5 Keyword Queries

((climat* or hydrolog* or ecosystem* or cloud*) and microphys*) or ((climat* or hydrolog* or ecosystem* or cloud*) and resilience) or ((climat* or hydrolog* or earth or ecosystem*) and "infrastructure system*") or ((climat* or hydrolog* or earth or ecosystem*) and "energy transition*") or "integrated assessment model*" or "energy-water-land" or "food-energy-water" or "climat* model*" or "hydrolog* model*" or "earth model*" or "earth system model*" or "ecosystem* model*" or "atmospher* (model* or simulation)" or "cloud resolv*" or (radiation cloud* atmospher*)

Working Group 5 Funding Queries

BER or "Biological & Environmental Research" or "Biological and Environmental Research" or "ARM" or "Atmospheric Radiation Measurement" or "ASR" or "Atmospheric System Research" or "RGMA" or "Regional and Global Model Analysis" or "ESMD" or "Earth System Model Development" or "RGCM" or "Regional and Global Climate Modeling" or "ESM" or "Earth System Modeling"

Appendix D
Request For Information
U.S. Department of Energy: Assessing the National and International Standing of BER Basic Research

Agency: Office of Science, Biological and Environmental Research Program, Department of Energy.

Action: Request For Information

Summary: The Biological and Environmental Research (BER) Program, as DOE's coordinating office for research on biological systems, bioenergy, environmental science, and Earth system science, is seeking input on technical and logistical pathways that would enhance the BER research portfolio in comparison to similar international research efforts.

Dates: Written comments and information are requested on or before October 31, 2021.

Addresses: Interested persons may submit comments by email only. Comments must be sent to BERACRFI@ science.doe.gov with the subject line "BER research benchmarking."

For further information, contact: Dr. Tristram O. West, (301) 903–5155, Tristram.west@science.doe.gov.

Supplementary information: A charge was issued from the Director of Office of Science on October 8, 2020, to the BER Advisory Committee (BERAC) to assess BER's standing in relation to related research efforts nationally and internationally, and to consider strategies that would increase BER's ability to conduct world-class science in core BER research areas. The Director's charge letter may be found here: https://science.osti.gov/ber/berac/Reports/Current-BERAC-Charges.

The information collected through this request, in addition to other informational sources, may be used by BERAC to develop strategies to further strengthen BER's research capabilities. The conclusions drawn from BERAC's effort are expected to serve as a benchmark for BER's standing in core research areas and provide strategies for improvement where appropriate.

Request For Information

The objective of this Request For Information is to gather information on BER's standing in relation to related research efforts occurring nationally and internationally, and how BER might increase its stature in conducting world-class basic science currently supported by BER (https://science.osti.gov/ber/Research). Supported research includes Atmospheric Science; Earth and Environmental System Modeling; Environmental Science; Bioenergy and Bioproducts; Plant and Microbial Genomics; Data Analytics and Management; and Scientific User-focused Infrastructure (i.e., DOE User Facilities, Computational Knowledgebase Platforms, Community Observational and Analytical Resources). Information is specifically requested on the status of current capabilities, partnerships, funding mechanisms, and workforce development specific to one or more of the aforementioned research areas. Answers or information related, but not limited, to the following questions are specifically requested:

- Within the BER-supported topical research areas and facility capabilities, in which areas and capabilities, presently or in the foreseeable future, does BER lead in the international community, and in which areas does leadership require strengthening? In identifying these areas, please consider their critical mission relevance, recent history, the status quo, observable trends, and evidence-based projections.
- Are there key international partnerships that could strengthen BER science output and increase global visibility of BER?
- Is there a preferred optimization for organizing research, collaboration, and funding mechanisms

among labs, universities, and other federal agencies to preserve and foster U.S. leadership with resource constraints? Are there other key efficiencies and balances that should be considered and modified to improve U.S. leadership in BER research areas?

- How can BER programs and facilities be structured and managed to create incentives that will attract and retain talented people deciding whether to pursue a scientific career, as well as mid-career scientists considering whether to stay in the U.S.?
- What are the key opportunities for BER in attracting and enhancing careers in BER-supported scientific fields?

While the questions provided above can help guide thinking on this topic, any input is welcome which may help DOE assess BER's international standing in the core research areas. The information provided through this request should be presented as specific strategies which DOE Office of Science could implement and track.

Signing Authority

This document of the Department of Energy was signed on August 11, 2021, by Dr. J. Stephen Binkley, Acting Director, Office of Science, pursuant to delegated authority from the Secretary of Energy. The document with the original signature and date is maintained by DOE. For administrative purposes only, and in compliance with requirements of the Office of the Federal Register, the undersigned DOE Federal Register Liaison Officer has been authorized to sign and submit the document in electronic format for publication, as an official document of the Department of Energy. This administrative process in no way alters the legal effect of this document upon publication in the Federal Register.

Signed in Washington, DC, on August 12, 2021.

Treena V. Garrett,
Federal Register Liaison Officer
U.S. Department of Energy
[FR Doc. 2021–17658 Filed 8–17–21; 8:45 am]
BILLING CODE 6450–01–P

Appendix E
References

Abraham, P. E., et al. 2016. "Transcript, Protein and Metabolite Temporal Dynamics in the CAM Plant *Agave*," *Nature Plants* **2**, 16178. DOI:10.1038/nplants.2016.178.

Albright, M. B. N., et al. 2020. "Differences in Substrate Use Linked to Divergent Carbon Flow During Litter Decomposition," *FEMS Microbiology Ecology*. **96**(8), fiaa135. DOI:10.1093/femsec/fiaa135.

Alivisatos, A. P., et al. 2015. "Microbiome. A Unified Initiative to Harness Earth's Microbiomes," *Science* **350**(6260), 507–8. DOI:10.1126/science.aac8480.

Alster, C. J., et al. 2020. "Embracing a New Paradigm for Temperature Sensitivity of Soil Microbes," *Global Change Biology* **26**(6), 3221–2. DOI:10.1111/gcb.15053.

AmAcad (American Academy of Arts & Sciences). 2020. *The Perils of Complacency, America at a Tipping Point in Science and Engineering*. Rice University's Baker Institute for Public Policy. (amacad.org/publication/perils-of-complacency).

Anber, U., et al. 2015. "Fog and Rain in the Amazon," *Proceedings of the National Academy of Sciences of the United States of America* **112**(37), 11473–7. DOI:10.1073/pnas.1505077112.

Arkin, A. P., et al. 2018. "KBase: The United States Department of Energy Systems Biology Knowledgebase," *Nature Biotechnology* **36**(7), 566–69. DOI:10.1038/nbt.4163.

ASCAC (Advanced Scientific Computing Advisory Committee). 2020. "Data-Intensive Science and High-Performance Computing." AI for Science Subcommittee. (science.osti.gov/-/media/ascr/ascac/pdf/meetings/202009/AI4Sci-ASCAC_202009.pdf).

Augustine, N. R., and N. Lane. 2021. "America on Edge: Settling for Second Place?" *Issues in Science and Technology*, Arizona State University.

Banda, D. M., et al. 2020. "Novel Bacterial Clade Reveals Origin of Form I Rubisco," *Nature Plants* **6**(9), 1158–66. DOI:10.1038/s41477-020-00762-4.

Bao, Z., et al. 2018. "Genome-Scale Engineering of *Saccharomyces Cerevisiae* with Single-Nucleotide Precision," *Nature Biotechnology* **36**(6), 505–08. DOI:10.1038/nbt.4132.

Bastiaanse, H., et al. 2019. "A Comprehensive Genomic Scan Reveals Gene Dosage Balance Impacts on Quantitative Traits in *Populus* Trees," *Proceedings of the National Academy of Sciences of the United States of America* **116**(27), 13690–99. DOI:10.1073/pnas.1903229116.

Bendall, M. L., et al. 2016. "Genome-Wide Selective Sweeps and Gene-Specific Sweeps in Natural Bacterial Populations," *The ISME Journal* **10**(7), 1589–601. DOI:10.1038/ismej.2015.241.

BERAC. 2010. *Grand Challenges for Biological and Environmental Research: A Long-Term Vision; A Report from the Biological and Environmental Research Advisory Committee March 2010 Workshop*, DOE/SC-0135. BERAC Steering Committee on Grand Research-Challenges for Biological and Environmental Research. (science.osti.gov/-/media/ber/pdf/Ber_ltv_report.pdf).

BERAC. 2013. *BER Virtual Laboratory: Innovative Framework for Biological and Environmental Grand Challenges; A Report from the Biological and Environmental Research Advisory Committee*, DOE/SC-0156, U.S. Department of Energy. (science.osti.gov/-/media/ber/berac/pdf/Reports/BER_VirtualLaboratory_finalwebLR.pdf).

BERAC. 2017. *Grand Challenges for Biological and Environmental Research: Progress and Future Vision; A Report from the Biological and Environmental Research Advisory Committee*, DOE/SC–0190, BERAC Subcommittee on Grand Research Challenges for Biological and Environmental Research. (science.osti.gov/~/media/ber/berac/pdf/Reports/BERAC-2017-Grand-Challenges-Report.pdf).

BERAC. 2018. *Scientific User Research Facilities and Biological and Environmental Research: Review and Recommendations; A Report from the Biological and Environmental Research Advisory Committee*, BERAC Subcommittee on Scientific User Research Facilities. (science.osti.gov/-/media/ber/pdf/community-resources/2018/BERAC_UserFacilities_Report.pdf).

BERAC COV. 2022. *Report to the Biological and Environmental Research Advisory Committee by the Committee of Visitors for the Review of the Biological Systems Science Division; Review of Fiscal Years 2017, 2018, 2019, and 2020.* (science.osti.gov/-/media/ber/berac/pdf/Reports/2021-BSSD-COV-Report_2022-02-04.pdf).

BESAC. 2021. *Can the US Compete in Basic Energy Sciences*? A Report of the BESAC Subcommittee on International Benchmarking. (science.osti.gov/-/media/bes/pdf/reports/2021/International_Benchmarking-Report.pdf).

Bewg, W.P., et al. 2022. "Multiplex Knockout of Trichome-Regulating MYB Duplicates in Hybrid Poplar Using a Single gRNA," *Plant Physiology* **189**(2), 516–26. DOI:10.1093/plphys/kiac128.

Bhattacharjee, B., et al. 2020. "Visualizing Microbial Community Dynamics via a Controllable Soil Environment," *mSystems* **5**(1), e00645–19. DOI:10.1128/mSystems.00645-19.

Biswal, A. K., et al. 2018. "Sugar Release and Growth of Biofuel Crops are Improved by Downregulation of Pectin Biosynthesis," *Nature Biotechnology* **36**(3), 249–57. DOI:10.1038/nbt.4067.

Blazewicz, S. J., et al. 2020. "Taxon-Specific Microbial Growth and Mortality Patterns Reveal Distinct Temporal Population Responses to Rewetting in a California Grassland Soil," *The ISME Journal* **14**(6), 1520–32. DOI:10.1038/s41396-020-0617-3.

Boucher, O., et al. 2013. *Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* The Intergovernmental Panel on Climate Change. (ipcc.ch/report/ar5/wg1/clouds-and-aerosols/).

Brown, C. T., et al. 2015. "Unusual Biology Across a Group Comprising More Than 15% of Domain Bacteria," *Nature* **523**(7559), 208–11. DOI:10.1038/nature14486.

Burke, A., A. Okrent, and K. Hale. 2022. "The State of U.S. Science and Engineering 2022," *Science and Engineering Indicators*. National Center for Sciences and Engineering Statistics.

Caldwell, P. M., et al. 2021. "Convection-Permitting Simulations with the E3SM Global Atmosphere Model," *Journal of Advances in Modeling Earth Systems* **13**(11), e2021MS002544. DOI:10.1029/2021MS002544.

Calvin, K., et al. 2019. "GCAM V5.1: Representing the Linkages between Energy, Water, Land, Climate, and Economic Systems," *Geoscientific. Model Development.* **12**(2), 677–98. DOI:10.5194/gmd-12-677-2019.

Carlson, H. K., et al. 2020. "Selective Carbon Sources Influence the End Products of Microbial Nitrate Respiration," *The ISME Journal* **14**(8), 2034–45. DOI:10.1038/s41396-020-0666-7.

Carper, D., et al. 2021. "Cultivation the Bacterial Microbiota of *Populus* Roots," *mSystems* **6**(3), e01306-20. DOI:10.1128/mSystems.01306-20.

Čermák, T., et. al. 2017. "A Multipurpose Toolkit to Enable Advanced Genome Engineering in Plants," *The Plant Cell* **29**(6), 1196–1217. DOI:10.1105/tpc.16.00922.

Chen, C., et al. 2022. "CO_2 Fertilization of Terrestrial Photosynthesis Inferred from Site to Global Scales," *Proceedings of the National Academy of Sciences of the United States of America* **119**(10). e2115627119, DOI:10.1073/pnas.2115627119.

Chen, K., et al. 2017. "Thermosensitivity of Growth is Determined by Chaperone-Mediated Proteome Reallocation," *Proceedings of the National Academy of Sciences of the United States of America* **114**(43), 11548–53. DOI:10.1073/pnas.1705524114.

Chui, M., et.al. 2020. "The Bio Revolution: Innovations Transforming Economies, Societies, and Our Lives," *McKinsey Global Institute.*

CNBC. 2022, March 25. "CNBC Exclusive: CNBC Transcript: United States Treasury Secretary Janet Yellen Speaks with CNBC's 'Squawk Box' Today." (www.cnbc.com/2022/03/25/cnbc-exclusive-cnbc-transcript-united-states-treasury-secretary-janet-yellen-speaks-with-cnbcs-squawk-box-today.html)

De Smet, A., et al. 2021. "Great Attrition or Great Attraction—the Choice Is Yours," *McKinsey & Company*.

Ding, Y., et al. 2021. "Getting Back to the Grass Roots: Harnessing Specialized Metabolites for Improved Crop Stress Resilience," *Current Opinion in Biotechnology* **70**, 174–86. DOI:10.1016/j.copbio.2021.05.010.

Dixon, R. A., and J. Barros 2019. "Lignin Biosynthesis: Old Roads Revisited and New Roads Explored," *Open Biology* **9**(12), 190215. DOI:10.1098/rsob.190215.

Domeignoz-Horta, L. A., et al. 2020. "Microbial Diversity Drives Carbon Use Efficiency in a Model Soil," *Nature Communications* **11**(1), 3684. DOI:10.1038/s41467-020-17502-z.

Dossani, Z.Y., et al. 2017. "A Combinatorial Approach to Synthetic Transcription Factor-Promoter Combinations for Yeast Strain Engineering," *Yeast.* **35**(3), 273–80. DOI:10.1002/yea.3292.

Dumitrache, A., et al. 2017. "Cellulose and Lignin Colocalization at the Plant Cell Wall Surface Limits Microbial Hydrolysis of *Populus* Biomass," *Green Chemistry* **19**(9), 2275–85. DOI:10.1039/c7gc00346c.

Eloe-Fadrosh, E. A., et al. 2016. "Global Metagenomic Survey Reveals a New Bacterial Candidate Phylum in Geothermal Springs," *Nature Communications* **7**, 10476. DOI:10.1038/ncomms10476.

Evans, L., et al. 2014. "Population Genomics of *Populus trichocarpa* Identifies Signatures of Selection and Adaptive Trait Associations," *Nature Genetics.* **46**, 1089–1096. DOI:1038/ng.3075.

Feldman, D. R., et al. 2015. "Observational Determination of Surface Radiative Forcing by CO_2 from 2000 to 2010," *Nature* **519**(7543), 339–43. DOI:10.1038/nature14240.

Fiedler, T., et al. 2021. "Business Risk and the Emergence of Climate Analytics," *Nature Climate Change* **11**(2), 87–94. DOI:10.1038/s41558-020-00984-6.

Forster, P., T., et al. 2021. "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis," Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 923–1054. DOI:10.1017/9781009157896.009.

FSOC. 2021. "2021 Financial Stability Oversight Council Annual Report," *U.S. Treasury.* (home.treasury.gov/system/files/261/FSOC2021AnnualReport.pdf).

Garst, A., et al. 2017. "Genome-Wide Mapping of Mutations at Single-Nucleotide Resolution for Protein, Metabolic and Genome Engineering," *Nature Biotechnology* **35,** 48–55. DOI:10.1038/nbt.3718.

Geernaert, G. 2021, October. "EESSD Director Gary Geernaert Presentation to BERAC." (science.osti.gov/-/media/ber/berac/pdf/202110/Geernaert_BERAC_202110.pdf).

Gibbs, D., and J. Wagner. 2021. *Inclusion and Diversity Workshop: Enhancing Organizational Effectiveness Through Inclusive Diversity*. National Laboratory Directors' Council. (nationallabs.org/site/wp-content/uploads/2021/12/21-50571_Report_Workshop_R9.pdf).

Gilna, P., et al. 2017. "Progress in Understanding and Overcoming Biomass Recalcitrance: A Bioenergy Science Center (BESC) Perspective," *Biotechnology for Biofuels* **10**(1), 285. DOI:10.1186/s13068-017-0971-1.

Ha, P. T., et al. 2017. "Syntrophic Anaerobic Photosynthesis Via Direct Interspecies Electron Transfer," *Nature Communications* **8**, 13924. DOI:10.1038/ncomms13924.

Haitjema, C. H., et al. 2017. "A Parts List for Fungal Cellulosomes Revealed by Comparative Genomics," *Nature Microbiology* **2**, 17087. DOI:10.1038/nmicrobiol.2017.87.

Harrington et al. 2018. "Programmed DNA Destruction by Miniature CRISPR-Cas14 Enzymes." *Science* **362**(6416), 839–42. DOI:10.1126/science.aav4294.

Hedlund, B.P., et al. 2014. "Impact of Single-Cell Genomics and Metagenomics on the Emerging View of Extremophile Microbial Dark Matter," *Extremophiles* **18,** 865–875. DOI:10.1007/s00792-014-0664-7.

Huang, P., et al. 2017. "*Sparse Panicle1* is Required for Inflorescence Development in *Setaria viridis* and Maize," *Nature Plants* **3**, 17054. DOI:10.1038/nplants.2017.54.

IHGSC (International Human Genome Sequencing Consortium). 2001. "Initial Sequencing and Analysis of the Human Genome," *Nature* **409**(6822), 860–921. DOI:10.1038/35057062.

Ing, N., et al. 2021. "A Multiplexed Nanostructure-Initiator Mass Spectrometry (NIMS) Assay for Simultaneously Detecting Glycosyl Hydrolase and Lignin Modifying Enzyme Activities," *Scientific Reports* **11**(1), 11803. DOI:10.1038/s41598-021-91181-8.

IPCC. 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. DOI:10.1017/9781009157896.

Jastrow, J. D., and R. M. Miller. 1998. "Soil Aggregate Stabilization and Carbon Sequestration: Feedbacks through Organomineral Associations," *Soil Processes and the Carbon Cycle,* 207–23. DOI:10.1201/9780203739273.

Jumper, J., et al. 2021. "Highly Accurate Protein Structure Prediction with AlphaFold," *Nature.* **596**, 583–89. DOI:10.1038/s41586-021-03819-2.

Junginger, H.M., et al. 2019. "The Future of Biomass and Bioenergy Deployment and Trade: A Synthesis of 15 Years IEA Bioenergy Task 40 on Sustainable Bioenergy Trade," *Wiley Online Library.* DOI:10.1002/bbb.1993.

Karim, A.S., et al. 2020. "*In Vitro* Prototyping and Rapid Optimization of Biosynthetic Enzymes for Cell Design," *Nature Chemical Biology* **16,** 912–19. DOI:10.1038/s41589-020-0559-0.

Kasanke, C. P., et al. 2020. "Can Switchgrass Increase Carbon Accrual in Marginal Soils? The Importance of Site Selection," *GCB Bioenergy* **13**(2), 320–35. DOI:10.1111/gcbb.12777.

King, Z. A., et al. 2016. "Bigg Models: A Platform for Integrating, Standardizing and Sharing Genome-Scale Models," *Nucleic Acids Research* **44**(D1), D515–22. DOI:10.1093/nar/gkv1049.

Kitano, H. 2000. "Perspectives on Systems Biology," *New Generation Computing* **18**(3), 199–216. DOI:10.1007/BF03037529.

Klein, S. A., and A. Hall. 2015. "Emergent Constraints for Cloud Feedbacks," *Current Climate Change Reports* **1**(4), 276–87. DOI:10.1007/s40641-015-0027-1.

Kosina, S. M., et al. 2021. "Biofilm Interaction Mapping and Analysis (BIMA) of Interspecific Interactions in *Pseudomonas* Co-Culture Biofilms," *Frontiers in Microbiology* **12**, 757856. DOI:10.3389/fmicb.2021.757856.

Krause, D. J., et al. 2018. "Functional and Evolutionary Characterization of a Secondary Metabolite Gene Cluster in Budding Yeasts," *Proceedings of the National Academy of Sciences of the United States of America* **115**(43), 11030–35. DOI:10.1073/pnas.1806268115.

Lal, P. B., et al. 2021. Erratum for Lal et al., "Improving Mobilization of Foreign DNA into *Zymomonas mobilis* Strain ZM4 by Removal of Multiple Restriction Systems," *Applied Environmental Microbiology* **87**(22), e0180521. DOI:10.1128/AEM.01805-21.

Levy, A., et al. 2018. "Genomic Features of Bacterial Adaptation to Plants," *Nature Genetics* **50**(1), 138–50. DOI:10.1038/s41588-017-0012-9.

Lian, J., et al. 2019. "Multi-Functional Genome-Wide CRISPR System for High Throughput Genotype-Phenotype Mapping," *Nature Communications* **10**(1), 5794. DOI:10.1038/s41467-019-13621-4.

Liao, H. L., et al. 2019. "Fungal Endophytes of *Populus trichocarpa* Alter Host Phenotype, Gene Expression, and Rhizobiome Composition," *Molecular Plant-Microbe Interactions* **32**(7), 853–64. DOI:10.1094/MPMI-05-18-0133-R.

Liew, F.E., et al. 2022. "Carbon-Negative Production of Acetone and Isopropanol by Gas Fermentation at Industrial Pilot Scale," *Nature Biotechnology* **40,** 335–44. DOI:10.1038/s41587-021-01195-w.

Liu, W., et al. 2020. "Correlative Surface Imaging Reveals Chemical Signatures for Bacterial Hotspots on Plant Roots," *Analyst* **145**(2), 393–401. DOI:10.1039/c9an01954e.

Lovell, J. T., et al. 2021. "Genomic Mechanisms of Climate Adaptation in Polyploid Bioenergy Switchgrass," *Nature* **590**(7846), 438–44. DOI:10.1038/s41586-020-03127-1.

Markowitz, V. M., et al. 2015. "Ten Years of Maintaining and Expanding a Microbial Genome and Metagenome Analysis System," *Trends in Microbiology* **23**(11), 730–41. DOI:10.1016/j.tim.2015.07.012.

Martin, F., et al. 2008. "The Genome of *Laccaria bicolor* Provides Insights into Mycorrhizal Symbiosis," *Nature* **452**, 88–92. DOI:10.1038/nature06556.

Metcalfe, K. S., et al. 2021. "Experimentally-Validated Correlation Analysis Reveals New Anaerobic Methane Oxidation Partnerships with Consortium-Level Heterogeneity in Diazotrophy," *The ISME Journal* **15**(2), 377–96. DOI:10.1038/s41396-020-00757-1.

Min, S. K., et al. 2011. "Human Contribution to More-Intense Precipitation Extremes," *Nature* **470**(7334), 378–81. DOI:10.1038/nature09763.

Ming, R. et al. 2015. "The Pineapple Genome and the Evolution of CAM Photosynthesis," *Nature Genetics* **47,** 1435–1442. DOI:10.1038/ng.3435.

Mondo, S. J., et al. 2017. "Widespread Adenine N6-Methylation of Active Genes in Fungi," *Nature Genetics* **49**(6), 964–68. DOI:10.1038/ng.3859.

Morrissey, E. M., et al. 2019. "Evolutionary History Constrains Microbial Traits across Environmental Variation," *Nature Ecology & Evolution* **3**(7), 1064–69. DOI:10.1038/s41559-019-0918-y.

Moss, R. H., et al. 2010. "The Next Generation of Scenarios for Climate Change Research and Assessment," *Nature* **463**(7282), 747–56. DOI:10.1038/nature08823.

Myers, T. A., et al. 2021. "Observational Constraints on Low Cloud Feedback Reduce Uncertainty of Climate Sensitivity," *Nature Climate Change* **11**(6), 501–07. DOI:10.1038/s41558-021-01039-0.

Nagy, L. G., et al. 2015. "Comparative Genomics of Early-Diverging Mushroom-Forming Fungi Provides Insights into the Origins of Lignocellulose Decay Capabilities," *Molecular Biology Evolution* **33**(4), 959–70. DOI:10.1093/molbev/msv337.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2000. "Experiments in International Benchmarking of US Research Fields.," The National Academies Press. DOI:10.17226/9784.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2007. Rising above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future. Washington, DC: The National Academies Press. DOI:10.17226/11463.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2018. "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space." The National Academies Press. DOI:10.17226/24938.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2022a. *Next Generation Earth System Science at National Science Foundation.* The National Academies Press. DOI:10.17226/9784.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2022b. *Physics of Life.* The National Academies Press. DOI:10.17226/26403.

National Research Council. 2006. *Midsize Facilities: The Infrastructure for Materials Research*. Washington, DC: The National Academies Press. DOI:10.17226/11336.

National Science Foundation. 2022. *Accelerating Innovations in Biomanufacturing Approaches through Collaboration Between NSF and the DOE-BETO funded Agile BioFoundry.* Program Solicitation NSF 22-549. (www.nsf.gov/pubs/2022/nsf22549/nsf22549.htm).

Nayfach, S., et al. 2021. "A Genomic Catalog of Earth's Microbiomes," *Nature Biotechnology* **39**(4), 499–509. DOI:10.1038/s41587-020-0718-6.

Naylor et al. 2020. "Soil Microbiomes Under Climate Change and Implications for Carbon Cycling," *Annual Review of Environment and Resources.* **45**, 29–59. DOI:10.1146/annurev-environ-012320-082720.

NIH (National Institutes of Health). 2015. *Patents as Proxies Revisited: NIH Innovation 2000-2013*. Battelle Technology Partnership Practice for the Academy of Radiology Research. (www.acadrad.org/wp-content/uploads/2017/04/Patents-as-Proxies-Revisited.March_.Final_.pdf).

Nikolaus, R., et al. 2022. *Dear Colleague Letter: Research Collaboration Opportunity in Europe for NSF Awardees. National Science Foundation.* (www.nsf.gov/pubs/2022/nsf22056/nsf22056.jsp).

Notonier, S., et al. 2021. "Metabolism of Syringyl Lignin-Derived Compounds in *Pseudomonas putida* Enables Convergent Production of 2-Pyrone-4,6-Dicarboxylic Acid," *Metabolic Engineering* **65**, 111–22, DOI:10.1016/j.ymben.2021.02.005.

NSB (National Science Board). 2007. *Science and Engineering Indicators.* National Science Foundation.

NSB (National Science Board). 2020. "Vision 2030: *National Science Board.* (nsf.gov/nsb/publications/2020/nsb202015.pdf).

OECD (Organisation for Economic Co-operation and Development). 2020. *Gross Domestic Spending on R&D*. (data.oecd.org/rd/gross-domestic-spending-on-r-d.htm).

Olsen, J. L., et al. 2016. "The Genome of the Seagrass *Zostera marina* Reveals Angiosperm Adaptation to the Sea," *Nature* **530**(7590), 331–5. DOI:10.1038/nature16548.

Ostrov, N., et al. 2016. "Design, Synthesis, and Testing Toward a 57-Codon Genome," *Science* **353**(6301), 819–22. DOI:10.1126/science.aaf3639.

Oyserman, B. O., et al. 2016. "Metatranscriptomic Insights on Gene Expression and Regulatory Controls in *Candidatus* Accumulibacter Phosphatis," *The ISME Journal* **10**(4), 810–22. DOI:10.1038/ismej.2015.155.

Paez-Espino, D., et al. 2016. "Uncovering Earth's Virome," *Nature* **536**(7617), 425–30. DOI:10.1038/nature19094.

Peralta-Yahya, P. P., et al. 2011. "Identification and Microbial Production of a Terpene-Based Advanced Biofuel," *Nature Communications* **2**, 483. DOI:10.1038/ncomms1494.

Pernice, M. C., et al. 2015. "Large Variability of Bathypelagic Microbial Eukaryotic Communities Across the World's Oceans," *The ISME Journal* **10**(4), 945–58. DOI:10.1038/ismej.2015.170.

Peter, M., et al. 2016. "Ectomycorrhizal Ecology is Imprinted in the Genome of the Dominant Symbiotic Fungus *Cenococcum geophilum*," *Nature Communications* **7**, 12662. DOI:10.1038/ncomms12662.

Qiao, K., et al. 2017. "Lipid Production in *Yarrowia lipolytica* Is Maximized by Engineering Cytosolic Redox Metabolism," *Nature Biotechnology* **35**(2), 173–77. DOI:10.1038/nbt.3763.

Ragauskas, A. J., et al. 2014. "Lignin Valorization: Improving Lignin Processing in the Biorefinery," *Science* **344**(6185), 1246843. DOI:10.1126/science.1246843.

Raissig, M. T., et al. 2017. "Mobile Mute Specifies Subsidiary Cells to Build Physiologically Improved Grass Stomata," *Science* **355**(6330), 1215–18. DOI:10.1126/science.aal3254.

Ramkumar, A. 2022, March 8. "Carbon-Transformation Startup LanzaTech is Going Public in $2.2 Billion SPAC Deal," *Wall Street Journal*.

Reed, P. M. et al. 2022. "MultiSector Dynamics: Scientific Challenges and a Research Vision for 2030, a Community of Practice Supported by the United States Department of Energy's Office of Science," *Zenodo*. DOI:10.5281/zenodo.6144309.

Riley, L. A., and A. M. Guss. 2021. "Approaches to Genetic Tool Development for Rapid Domestication of Non-Model Microorganisms," *Biotechnology for Biofuels and Bioproducts* **14**(1), 30. DOI:10.1186/s13068-020-01872-z.

Rinke, C., et al. 2013. "Insights into the Phylogeny and Coding Potential of Microbial Dark Matter," *Nature.* **499**, 431–37. DOI:10.1038/nature12352.

Saifuddin, M., et al. 2019. "Microbial Carbon Use Efficiency Predicted from Genome-Scale Metabolic Models," *Nature Communications* **10**(1), 3568. DOI:10.1038/s41467-019-11488-z.

Salvachua, D., et al. 2020. "Metabolic Engineering of *Pseudomonas putida* for Increased Polyhydroxyalkanoate Production from Lignin," *Microbial Biotechnology* **13**(3), 813. DOI:10.1111/1751-7915.13547.

Schellenberger, J., et al. 2011. "Quantitative Prediction of Cellular Metabolism with Constraint-Based Models: The COBRA Toolbox V2.0," *Nature Protocols* **6**(9), 1290–307. DOI:10.1038/nprot.2011.308.

Schulz, F., et al. 2017. "Giant Viruses with an Expanded Complement of Translation System Components," *Science* **356**(6333), 82–85. DOI:10.1126/science.aal4657.

Searle, S. and C. Malins. 2015. "A Reassessment of Global Bioenergy Potential in 2050," *Wiley Online Library.* DOI:10.1111/gcbb.12141.

Sebastian, J., et al. 2016. "Grasses Suppress Shoot-Borne Roots to Conserve Water During Drought," *Proceedings of the National Academy of Sciences of the United States of America* **113**(31), 8861–6. DOI:10.1073/pnas.1604021113.

Sekhon, R., et al. 2011. "Genome-Wide Atlas of Transcription During Maize Development," *The Plant Journal* **66**(4), 553–63. DOI:10.1111/j.1365-313X.2011.04527.

Sherwood, S. C., et al. 2020. "An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence," *Reviews of Geophysics* **58**(4), e2019RG000678. DOI:10.1029/2019RG000678.

Shih, P. M., et al. 2016. "A Robust Gene-Stacking Method Utilizing Yeast Assembly for Plant Synthetic Biology," *Nature Communications* **7**, 13215. DOI:10.1038/ncomms13215.

Shultz, D. 2020, March 26. "Why is Climate More Sensitive in the Latest Earth System Models?" Eos Science News by AGU. (eos.org/research-spotlights/how-river-capture-affects-the-evolution-of-aquatic-organisms).

Slater, S. C., et al. 2015. "The DOE Bioenergy Research Centers: History, Operations, and Scientific Output," *BioEnergy Research* **8**(3), 881–96. DOI:10.1007/s12155-015-9660-8.

Solomon, K. V., et al. 2016. "Early-Branching Gut Fungi Possess a Large, Comprehensive Array of Biomass-Degrading Enzymes," *Science* **351**(6278), 1192–5. DOI:10.1126/science.aad1431.

Steidinger, B. S., et al. 2019. "Climatic Controls of Decomposition Drive the Global Biogeography of Forest-Tree Symbioses," *Nature* **569**(7756), 404–08. DOI:10.1038/s41586-019-1128-0.

St. James, A. R., et al. 2021. "Linking Microbial *Sphagnum* Degradation and Acetate Mineralization in Acidic Peat Bogs: From Global Insights to a Genome-Centric Case Study," *The ISME Journal* **15**(1), 293–303. DOI:10.1038/s41396-020-00782-0.

Sun, L., et al. 2021. "Complete and Efficient Conversion of Plant Cell Wall Hemicellulose into High-Value Bioproducts by Engineered Yeast," *Nature Communications* **12**(1), 4975. DOI:10.1038/s41467-021-25241-y.

Tetard, L., et al. 2015. "Opto-Nanomechanical Spectroscopic Material Characterization," *Nature Nanotechnology* **10**(10), 870–7. DOI:10.1038/nnano.2015.168.

TOP500. 2022, May 30. "ORNL's Frontier First to Break the Exaflop Ceiling," (top500.org/news/ornls-frontier-first-to-break-the-exaflop-ceiling).

Trigg, S. A., et al. 2017. "CrY2H-seq: A Massively Multiplexed Assay for Deep-Coverage Interactome Mapping," *Nature Methods* **14**(8), 819–25. DOI:10.1038/nmeth.4343.

Tuskan, G.A., et al. 2006. "The Genome of Black Cottonwood, *Populus Trichocarpa* (Torr. & Gray)," *Science* **131**(5793), 1596–1604. DOI:10.1126/science.1128691.

Tyson, G., et al. 2004. "Community Structure and Metabolism Through Reconstruction of Microbial Genomes from the Environment," *Nature* **428,** 37–43. DOI:10.1038/nature02340.

UNESCO (United Nations Educational, Scientific, and Cultural Organization). 2022, August 10. *How Much Does Your Country Invest in R&D?* (uis.unesco.org/apps/visualisations/research-and-development-spending).

U.S. DOE. 2006. *Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda*, DOE/SC-0095. U.S. Department of Energy Office of Science. (genomicscience.energy.gov/wp-content/uploads/2021/10/b2bhighres63006.pdf).

U.S. DOE. 2014a. *U.S. Department of Energy Strategic Plan*, DOE/CF-0067. U.S. Department of Energy. (www.energy.gov/sites/default/files/2014/04/f14/2014_dept_energy_strategic_plan.pdf).

U.S. DOE. 2014b. *Research for Sustainable Bioenergy: Linking Genomic and Ecosystem Sciences Workshop Report,* DOE/SC-0167. U.S. Department of Energy Office of Science. (www.osti.gov/servlets/purl/1471545).

U.S. DOE. 2015a. *Biological Systems Science Division Strategic Plan 2015.* U.S. Department of Energy Office of Science. (genomicscience.energy.gov/wp-content/uploads/2021/09/BSSDStrategicPlan.pdf).

U.S. DOE, 2015b. *Lignocellulosic Biomass for Advanced Biofuels and Bioproducts: Workshop Report,* DOE/SC-0170. U.S. Department of Energy Office of Science. (genomicscience.energy.gov/wp-content/uploads/2021/10/BioenergyReport-February-20-2015LR.pdf).

U.S. DOE. 2017. *Research Priorities to Incorporate Terrestrial-Aquatic Interfaces in Earth System Models: Workshop Report*, DOE/SC-0187. U.S. Department of Energy Office of Science. (science.osti.gov/-/media/ber/pdf/community-resources/Terrestrial-Aquatic_Interfaces_report.pdf).

U.S. DOE. 2018a. *Climate and Environmental Sciences Division Strategic Plan 2018–2023,* DOE/SC–0192. U.S. Department of Energy Office of Science. (science.osti.gov/~/media/ber/pdf/workshop%20reports/2018_CESD_Strategic_Plan.pdf).

U.S. DOE. 2018b. *Disturbance and Vegetation Dynamics in Earth System Models: Workshop Report*, DOE/SC–0196. U.S. Department of Energy Office of Science. (science.osti.gov/-/media/ber/pdf/community-resources/2018/Disturbance_and_Vegetation_Dynamics_in_Earth_System_Models_Workshop.pdf).

U.S. DOE. 2018c. *U.S. Department of Energy Bioenergy Research Centers: 10-Year Retrospective: Breakthroughs and Impacts*. DOE/SC–0193. U.S. Department of Energy Office of Science. (genomicscience.energy.gov/bioenergy-research-centers-10-year-retrospective/).

U.S. DOE. 2019. *Open Watershed Science by Design: Leveraging Distributed Research Networks to Understand Watershed Systems: Workshop Report*, DOE/SC–0200. U.S. Department of Energy Office of Science. (science.osti.gov/-/media/ber/pdf/community-resources/2019/Open_Watersheds_By_Design.pdf).

U.S. DOE. 2020a. *U.S. Department of Energy Office of Science Biological and Environmental Research Environmental System Science: Funding Opportunity Announcement DE-FOA-0002392*. U.S. Department of Energy Office of Science Biological and Environmental Research. (science.osti.gov/-/media/grants/pdf/foas/2021/SC_FOA_0002392.pdf).

U.S. DOE. 2020b. *U.S. Department of Energy Free-Air CO_2 Enrichment Experiments: FACE Results, Lessons, and Legacy*, DOE/SC–0202. U.S. Department of Energy Office of Science. (ess.science.energy.gov/wp-content/uploads/2020/12/facereport2020.pdf).

U.S. DOE 2020c. *AI for Science: Report on the Department of Energy (DOE) Town Halls on Artificial Intelligence (AI) for Science.* U.S. Department of Energy Office of Science. (publications.anl.gov/anlpubs/2020/03/158802.pdf).

U.S. DOE. 2021a. *Biological Systems Science Division Strategic Plan.* U.S. Department of Energy Office of Science. (genomicscience.energy.gov/wp-content/uploads/2021/09/BSSD_Strategic_Plan_2021.pdf).

U.S. DOE. 2021b. *Lessons from the COVID Era and Visions for the Future. Report from the December 2020 Roundtable.* U.S. Department of Energy Office of Science. DOI:10.2172/1785683.

U.S. DOE 2021c. *Inclusion & Diversity Workshop: Enhancing Organizational Effectiveness Through Inclusive Diversity. Department of Energy Summary Report 2021.* National Laboratory Directors' Council. (nationallabs.org/site/wp-content/uploads/2021/12/21-50571_Report_Workshop_R9.pdf).

U.S. DOE. 2021d. *ARM Aerosol Measurement Science Group 2019 Strategic Planning Workshop Report*, ARM Aerosol Measurement Science Group, U.S. Department of Energy Office of Science. (www.arm.gov/publications/programdocs/doe-sc-arm-21-010.pdf).

U.S. DOE. 2022a. *U.S. Department of Energy National Virtual Biotechnology Laboratory Technical Report.* U.S. Department of Energy Office of Science. DOI:10.2172/1871217.

U.S. DOE. 2022b. *U.S. Department of Energy Office of Science Biological and Environmental Research Urban Integrated Field Laboratories (IFL) Funding Opportunity Announcement DE-FOA-0002581*. U.S. Department of Energy Office of Science Biological and Environmental Research. (science.osti.gov/-/media/grants/pdf/foas/2022/SC_FOA_0002581.pdf)

U.S. DOE 2022c. *U.S. Department of Energy Equity Action Plan.* U.S. Department of Energy. (www.energy.gov/sites/default/files/2022-04/DOE%20Equity%20Action%20Plan_Letterhead.pdf).

U.S. DOE 2022d. *U.S. Department of Energy Diversity, Equity, Inclusion, & Accessibility (DEIA) Strategic Plan 2022.* U.S. Department of Energy. (www.energy.gov/sites/default/files/2022-09/DOEDEIAStrategicPlan_1.pdf).

Velickovic, D., et al. 2018. "Observed Metabolic Asymmetry Within Soybean Root Nodules Reflects Unexpected Complexity in Rhizobacteria-Legume Metabolite Exchange," *The ISME Journal* **12**(9), 2335–38. DOI:10.1038/s41396-018-0188-8.

Victor, T. W., et al. 2020. "Lanthanide-Binding Tags for 3D X-Ray Imaging of Proteins in Cells at Nanoscale Resolution," *Journal of the American Chemical Society* **142**(5), 2145–49. DOI:10.1021/jacs.9b11571.

Voosen, P. 2020. "Earth's Climate Destiny Finally Seem More Clearly." *Science* **369**(6502), 354–55. DOI:10.1126/science.369.6502.354.

Wang, J., et al. 2016. "Amazon Boundary Layer Aerosol Concentration Sustained by Vertical Transport During Rainfall," *Nature* **539**(7629), 416–19. DOI:10.1038/nature19819.

Wannier, T.M., et al. 2020. "Improved Bacterial Recombineering by Parallelized Protein Discovery," *Proceedings of the National Academy of Sciences of the United States of America* **117**(24), 13689–98. DOI:10.1073/pnas.2001588117.

Web of Science. 2022, August 10. "Trusted Publisher-Independent Citation Database." *Web of Science Group*.

Westerhoff, H. V., and B. O. Palsson. 2004. "The Evolution of Molecular Biology into Systems Biology," *Nature Biotechnology* **22**(10), 1249–52, DOI:10.1038/nbt1020.

Wilhelm, R., et al. 2021. "Competitive Exclusion and Metabolic Dependency Among Microorganisms Structure the Cellulose Economy of an Agricultural Soil," *mBio* **12**(1), e03099–20. DOI:10.1128/mBio.03099-20.

WMO. 2020. *2020 State of Climate Services: Risk Information and Early Warning Systems,* World Meteorological Organization.

Woo, J., et al. 2021. "High-Throughput and High-Efficiency Sample Preparation for Single-Cell Proteomics Using a Nested Nanowell Chip," *Nature Communications* **12**, 6246. DOI: 10.1038/s41467-021-26514-2.

Woods, D. P., et al. 2017. "Establishment of a Vernalization Requirement in *Brachypodium distachyon* Requires Repressor of Vernalization," *Proceedings of the National Academy of Sciences of the United States of America* **114**(25), 6623–28. DOI:10.1073/pnas.1700536114.

World Bank. 2022, June. *Research and Development Expenditure (% of GDP)*, The World Bank. (data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS).

Wu, R., et al. 2021a. "Moisture Modulates Soil Reservoirs of Active DNA and RNA Viruses," *Communications Biology* **4**(1), 992. DOI:10.1038/s42003-021-02514-2.

Wu, R., et al. 2021b. "DNA Viral Diversity, Abundance, and Functional Potential Vary across Grassland Soils with a Range of Historical Moisture Regimes," *mBio* **12**(6), e0259521. DOI:10.1128/mBio.02595-21.

Xie, M., et al. 2020. "*Arabidopsis* C-Terminal Binding Protein *Angustifolia* Modulates Transcriptional Co-Regulation of *Myb46* and *Wrky33*," *New Phytologist* **228**(5), 1627–39. DOI:10.1111/nph.16826.

Xu, L., et al. 2018. "Drought Delays Development of the Sorghum Root Microbiome and Enriches for Monoderm Bacteria," *Proceedings of the National Academy of Sciences of the United States of America* **115**(18), E4284–E93. DOI:10.1073/pnas.1717308115.

Xu, P., et al. 2016. "Engineering *Yarrowia lipolytica* as a Platform for Synthesis of Drop-in Transportation Fuels and Oleochemicals," *Proceedings of the National Academy of Sciences of the United States of America* **113**(39), 10848–53. DOI:10.1073/pnas.1607295113.

Xu, Q., et al. 2016. "Dramatic Performance of *Clostridium thermocellum* Explained by Its Wide Range of Cellulase Modalities," *Science Advances* **2**(2), e1501254. DOI:10.1126/sciadv.1501254.

Yang, X., et al. 2017. "The *Kalanchoe* Genome Provides Insights into Convergent Evolution and Building Blocks of Crassulacean Acid Metabolism," *Nature Communications* **8**(1), 1899. DOI:10.1038/s41467-017-01491-7.

Yoo, C. G., et al. 2018. "Significance of Lignin S/G Ratio in Biomass Recalcitrance of *Populus trichocarpa* Variants for Bioethanol Production," *ACS Sustainable Chemistry & Engineering* **6**(2), 2162–68. DOI:10.1021/acssuschemeng.7b03586.

Yu, H., and C. Liu, and R. A. Dixon 2021. "A Gene-Editing/Complementation Strategy for Tissue-Specific Lignin Reduction While Preserving Biomass Yield," *Biotechnology for Biofuels and Biotechnology* **14**(1), 175. DOI:10.1186/s13068-021-02026-5.

Zegeye, E. K., et al. 2019. "Selection, Succession, and Stabilization of Soil Microbial Consortia," *mSystems* **4**(4). DOI:10.1128/mSystems.00055-19.

Zeitoun, R. I., et al. 2015. "Multiplexed Tracking of Combinatorial Genomic Mutations in Engineered Cell Populations," *Nature Biotechnology* **33**(6), 631–7. DOI:10.1038/nbt.3177.

Zelinka, M. D., and S. A. Klein, and D. L. Hartmann 2012a. "Computing and Partitioning Cloud Feedbacks Using Cloud Property Histograms. Part I: Cloud Radiative Kernels," *Journal of Climate* **25**(11), 3715–35. DOI:10.1175/jcli-d-11-00248.1.

Zelinka, M. D., and S. A. Klein, and D. L. Hartmann 2012b. "Computing and Partitioning Cloud Feedbacks Using Cloud Property Histograms. Part II: Attribution to Changes in Cloud Amount, Altitude, and Optical Depth," *Journal of Climate* **25**(11), 3736–54. DOI:10.1175/jcli-d-11-00249.1.

Zelinka, M. D., et al. 2013. "Contributions of Different Cloud Types to Feedbacks and Rapid Adjustments in CMIP5," *Journal of Climate* **26**(14), 5007-27. DOI:10.1175/JCLI-D-12-00555.1.

Zelinka, M. D., et al. 2020. "Causes of Higher Climate Sensitivity in CMIP6 Models," *Geophysical Research Letters* **47**(1). DOI:10.1029/2019gl085782.

Zengler et al. 2019. "EcoFABs: Advancing Microbiome Science Through Standardized Fabricated Ecosystems," *Nature Methods* **16**, 567–571. DOI:10.1038/s41592-019-0465-0.

Zhang, F., J. M. Carothers, and J. D. Keasling 2012. "Design of a Dynamic Sensor-Regulator System for Production of Chemicals and Fuels Derived from Fatty Acids," *Nature Biotechnology* **30**(4), 354–59. DOI:10.1038/nbt.2149.

Zhuo, C., et al. 2022. "Developmental Changes in Lignin Composition Are Driven by Both Monolignol Supply and Laccase Specificity," *Science Advances* **8**(10), eabm814w5. DOI:10.1126/sciadv.abm8145.

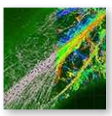
Appendix F

Image Credits

Executive Summary

Grid view of Earth from the atmospheric component of the Energy Exascale Earth System Model (E3SM). [Reprinted under a Creative Commons license (CC BY-NC-ND 4.0) from Rasch, P.J., et al. 2019. "An Overview of the Atmospheric Component of the Energy Exascale Earth System Model," *JAMES: Journal of Advances in Modeling Earth Systems* **11**(8), 2377-2411.]

Headwaters of Snake River. [Courtesy Environmental Molecular Sciences Laboratory]



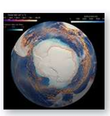
Plant protein dynamics. [Courtesy University of Delaware]

A soil-grown root system. [Courtesy Carnegie Institute for Science]

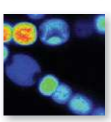
Chapter 1: Introduction

Researcher collects *Miscanthus* root samples. [Courtesy Center for Advanced Bioenergy and Bioproducts Innovation]

Magnified view of a red pine (*Pinus resinosa*) root and associated microbiome. [Courtesy Environmental Molecular Sciences Laboratory]



Modeled ice speed for the Antarctic ice sheet. [Courtesy Los Alamos National Laboratory]



Photobleached cell. [Courtesy University of Colorado–Boulder and University of Illinois–Chicago]

Chapter 2: Bioenergy and Environmental Microbiomes

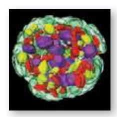
Microbes colonizing poplar roots. [Courtesy Oak Ridge National Laboratory]

Researchers sample soils to understand how climate change affects microbial growth efficiency and soil carbon stocks. [Courtesy University of Massachusetts–Amherst]

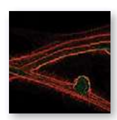
A sorghum field with bagged flowers to prevent pollen exchange. [Courtesy Lawrence Berkeley National Laboratory]

Plants at different stages of growth. [Courtesy Oak Ridge National Laboratory]

Chapter 3: Biosystems Design



Cryo-soft X-ray tomography of a reconstructed green alga cell. [From Roth, M.S., et al. 2017. "Chromosome-Level Genome Assembly and Transcriptome of the Green Alga *Chromochloris zofingiensis* Illuminates Astaxanthin Production," *PNAS* **114**(21), E4296-E4305.]



Transgenic roots of *Medicago truncatula* with nodules formed by its symbiont (*Sinorhizobium meliloti*). [Courtesy University of Florida]

Illustration of engineered biosynthetic metabolic pathways. [Reprinted by permission from Springer Nature from Karim, A. S., et al. 2020. "*In Vitro* Prototyping and Rapid Optimization of Biosynthetic Enzymes for Cell Design," *Nature Chemical Biology* **16**(8), 912–19. Copyright 2020.]

Yeast strain *Yarrowia lipolytica*. [Courtesy University of Tennessee]

Chapter 4: Environmental System Science

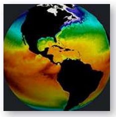
East River watershed in upper Colorado River Basin. [Courtesy Lawrence Berkeley National Laboratory]

Catlett Islands water sediment site. [Courtesy Pacific Northwest National Laboratory]

The Spruce and Peatland Responses Under Changing Environments (SPRUCE) research site located in northern Minnesota. [Courtesy Oak Ridge National Laboratory]


Next-Generation Ecosystem Experiments (NGEE) Tropics field site in Puerto Rico. [Courtesy Lawrence Berkeley National Laboratory]

Chapter 5: Climate Science


E3SM model of sea surface temperature. [Courtesy E3SM]


Fair weather clouds studied as part of the Cloud and Land Surface Interaction Campaign by the Atmospheric Radiation Measurement (ARM) user facility. [Courtesy ARM]


Road junction. [Courtesy Getty Images]

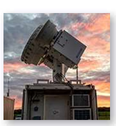

Instruments from ARM user facility's Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign in the Sierras de Córdoba mountain range of north-central Argentina. [Courtesy ARM]

Chapter 6: Enabling Infrastructure

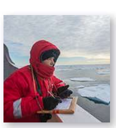

Magnified view of the mineral olivine forsterite. [Courtesy Pacific Northwest National Laboratory]


Ca-Ca3 AmeriFlux Tower in British Columbia. [Courtesy AmeriFlux]

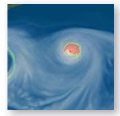

Researcher loads a DNA sequencer. [Courtesy Lawrence Berkeley National Laboratory]


ARM cloud radar in Brazil. [Courtesy ARM]

Chapter 7: Integrative Science


MOSAiC researcher. [Reprinted with permission from the Alfred Wegener Institute/Esther Horvath under a Creative Commons License.]


Computer simulations of the T4 lysozyme wrapped around a bacterial cell wall. [Courtesy Environmental Molecular Sciences Laboratory]


E3SM Category 5 hurricane simulation. [Courtesy E3SM]


Researcher working on lignin digestibility. [Courtesy Great Lakes Bioenergy Research Center]

Chapter 8: People, Partnerships, and Productivity


Researchers examine plant-microbe interactions to improve biomass feedstock growth. [Courtesy DOE Joint Genome Institute]


A mobile atmospheric observatory operating in downtown Houston [Courtesy ARM]

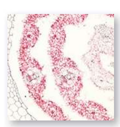

X-ray crystallographer analyzes SARS-CoV-2 proteins at the Advanced Photon Source. [Courtesy Argonne National Laboratory]


Sampling during the MOSAiC expedition. [Reprinted with permission from the Alfred Wegener Institute/Torsten Sachs under a Creative Commons License]

Chapter 9: Reflections and Conclusions


Artist interpretation of the enzyme enoyl-CoA carboxylase/reductase. [Courtesy SLAC National Accelerator Laboratory]


Section of the Columbia River watershed. [Courtesy Pacific Northwest National Laboratory]


BdTHX1 expression (red, immunolabeling) in the leaf sheath of *Brachypodium*. [Courtesy Great Lakes Bioenergy Research Center]


E3SM simulation of the Arctic Ocean showing surface ocean currents, temperatures, and sea-ice concentration. [Courtesy E3SM]

Appendix G

Acronyms and Abbreviations

3CLpro	3 chymotrypsin-like protease
AAF	ARM Aerial Facility
AcceLNet	Accelerating Research through International Network-to-Network Collaborations
ACTRIS	Aerosol, Clouds, and Trace Gases Research Infrastructure
AI	artificial intelligence
AI4ESP	AI for Earth System Predictability
ALCF	Argonne Leadership Computing Facility
AMF	ARM Mobile Facility
AMIP	Atmospheric Model Intercomparison Project
AMP	AmeriFlux Management Project
API	Application Programming Interface
ARM	Atmospheric Radiation Measurement user facility
ARPA-E	Advanced Research Projects Agency-Energy
ASCR	DOE Advanced Scientific Computing Research program
ASR	Atmospheric System Research
BER	DOE Biological and Environmental Research program
BERAC	Biological and Environmental Research Advisory Committee
BES	DOE Basic Energy Sciences program
BESAC	Basic Energy Sciences Advisory Committee
BESC	BioEnergy Science Center
BETO	DOE Bioenergy Technologies Office
BGI	Beijing Genomics Institute
BRC	Bioenergy Research Center
BSL-3	biosafety level 3
BSSD	Biological Systems Science Division
CABBI	Center for Advanced Bioenergy and Bioproducts Innovation
CBI	Center for Bioenergy Innovation
CCSEM-EDX	computer-controlled scanning electron microscope with energy dispersive X-ray spectroscopy
CEDA	UK's Center for Environmental Data Analysis
CESM	NCAR Community Earth System Model
CMIP	Coupled Model Intercomparison Project
CO_2	carbon dioxide
COMPASS	Coastal Observations, Mechanisms, and Predictions Across Systems and Scales
COSORE	community database for continuous soil respiration
COVID-19	coronavirus disease 2019
CRAGE	chassis (or strain)-independent recombinase-assisted genome engineering
CRISPR	clustered regularly interspaced short palindromic repeats
CSP	Community Science Program
DEI	diversity, equity, and inclusion
DestinE	European Commission's Destination Earth
DFG	German Research Foundation
DKRZ	German Climate Computing Center
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
E3SM	Energy Exascale Earth System Model
ECMWF	European Centre for Medium Range Weather Forecasting
ECP	DOE Exascale Computing Project
ECRP	Early Career Research Program
ECS	equilibrium climate sensitivity
EERE	DOE Office of Energy Efficiency and Renewable Energy
EESM	Earth and Environmental Systems Modeling

EESSD	Earth and Environmental Systems Sciences Division
ELM	E3SM Land Model
EMSL	Environmental Molecular Sciences Laboratory
ENA	Eastern North Atlantic
ENIGMA	Ecosystems and Networks Integrated with Genes and Molecular Assemblies
ESGF	Earth System Grid Federation
ESM	Earth System Model
ESS	Environmental System Science
ESS-DIVE	Environmental System Science Data Infrastructure for a Virtual Ecosystem
EU	European Union
EUSAAR	European Supersites for Atmospheric Aerosol Research
FACE	Free-Air CO_2 Enrichment
FAIR	findable, accessible, interoperable, and reusable
FATES	Functionally Assembled Terrestrial Ecosystem Simulator
FICUS	Facilities Integrating Collaborations for User Science
FOA	funding opportunity announcemen
FY	fiscal year
FREDA	FT-MS R Exploratory Data Analysis
GCAM	Global Change Analysis Model
GCIMS	Global Change Intersectoral Modeling System
GFDL	NOAA Geophysical Fluid Dynamics Laboratory
GLBRC	Great Lakes Bioenergy Research Center
GSP	Genomic Science Program
HGP	Human Genome Project
IAM	integrated assessment modeling
ICON	Icosahedral Nonhydrostatic Weather and Climate Model
ICOS	Europe's Integrated Carbon Observation System
IDEAS	Interoperable Design of Extreme-scale Applications Software
IFL	Integrated Field Laboratory
ILAMB	International Land Model Benchmarking
IM_3	Integrated Multisector Multiscale Modeling
IMG/M	Integrated Microbial Genomics and Microbiomes
Input4MIPS	Input datasets for Model Intercomparison Projects
IPCC	Intergovernmental Panel on Climate Change
JBEI	Joint BioEnergy Institute
JGI	DOE Joint Genome Institute
KBase	DOE Systems Biology Knowledgebase
LDRD	laboratory-directed research and development
LTAR	Long-Term Agroecosystem Research Network
LTER	Long-Term Ecological Research Network
m-CAFEs	Microbial Community Analysis and Functional Evaluation in Soils
MIP	model intercomparison project
MKG	Microsoft Knowledge Graph
ML	machine learning
ModEx	model-experiment
MOSAiC	Multidisciplinary drifting Observatory for the Study of Arctic Climate
MS	mass spectrometry
nanoPOTS	nanodroplet processing in one-pot for trace samples
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NCAR	National Center for Atmospheric Research
NEON	National Ecological Observatory Network
NERSC	National Energy Research Scientific Computing Center
NEXUS	Network for Execution of User Science
NGEE	Next-Generation Ecosystem Experiments

NICAM	Nonhydrostatic ICosahedral Atmospheric Model
NIH	National Institutes of Health
NMDC	National Microbiome Data Collaborative
NOAA	National Oceanic and Atmospheric Administration
NSA	Northern Slope of Alaska
NSB	National Science Board
NSF	National Science Foundation
NSLS-II	National Synchrotron Light Source II
NREL	National Renewable Energy Laboratory
NVBL	National Virtual Biotechnology Laboratory
OECD	Organisation for Economic Co-operation and Development
OLCF	Oak Ridge Leadership Computing Facility
ORNL	Oak Ridge National Laboratory
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PFLOTRAN	Parallel Reactive Flow and Transport model
PI	principal investigator
PLpro	papain-like protease
PMP	PCMDI Metrics Package
PNNL	Pacific Northwest National Laboratory
PuRe	Public Reusable Research
QPSI	Quantitative Plant Science Initiative
R&D	research and development
RENEW	Reaching a New Energy science Workforce
RFI	Request For Information
SARS-CoV-2	severe acute respiratory syndrome coronavirus 2
SBIR	Small Business Innovation Research
SciDAC	Scientific Discovery Through Advanced Computing
SCREAM	Simple Cloud-Resolving E3SM Atmosphere Model
SFA	Science Focus Area
SGP	Southern Great Plains
SPAC	Special Purpose Acquisition Company
SPRUCE	Spruce and Peatland Responses Under Changing Environments
STTR	Small Business Technology Tra
TALENs	transcription activator-like effector nucleases
TBS	tethered balloon system
TEAMS	Trial Ecosystems for the Advancement of Microbiome Science
TERRA	Transportation Energy Resources from Renewable Agriculture
TMT	tandem mass tag
TRACER	Tracking Aerosol Convection Interactions Experiment
TRL	Technology Readiness Level
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USDA	U.S. Department of Agriculture
USGS	United States Geological Survey
USQCD	U.S. Lattice Quantum Chromodynamics computing project
VSV	vesicular stomatitis virus
WCRP	World Climate Research Programme
WDCC	World Data Center for Climate
WGCM	WCRP Working Group on Coupled Modelling
WHONDRS	Worldwide Hydrobiogeochemical Observation Network for Dynamic River Systems
WoS	Web of Science